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SOFAR FLOATS IN MODE, FINAL REPORT OF FLOAT TRAJECTORY DATA.(U)

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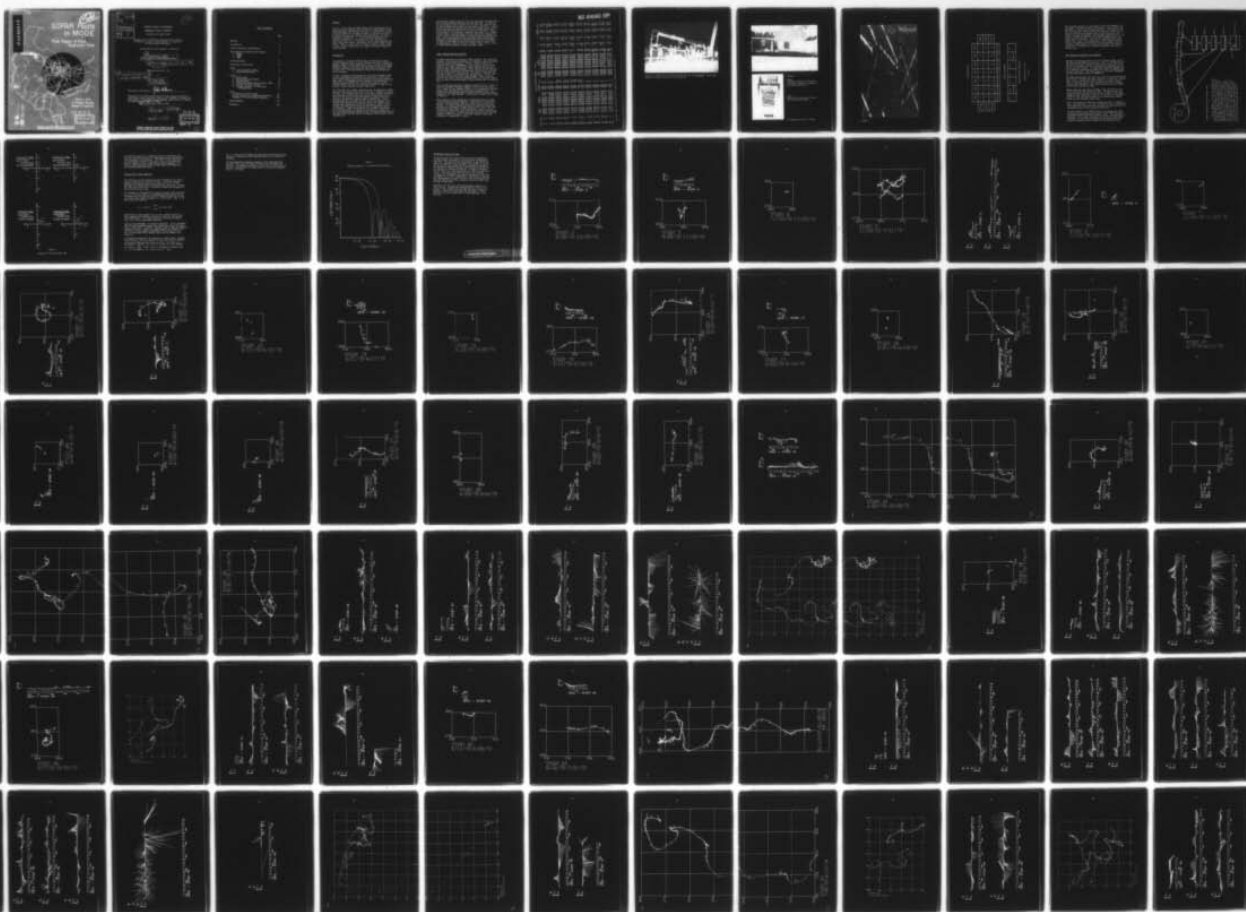
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SOFAR Floats in MODE

Final Report of Float
Trajectory Data

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TABLE OF CONTENTS

	Page
Abstract	1
Introduction	1
Signal Transmission and Reception	2
Data Processing Procedures and Programs	8
1. GRIND	
2. CRUNCH	
3. TRACK	
Tracking Accuracy	10
Calculation of Velocities	13
Tables	
1. Float Statistical Summary	3
2. Channel-Period Table	7
Figures	
1. Float Launch	4
2. Receiver Rack and Station	5
3. Drum Recording	6
4. Finding the Signal Time of Arrival (TOA)	9
5. Accuracy of Float Positions	12
6. Frequency Response of Low Passed Differentiator	15
Plots	
Trajectories and Stick Plots	17
Ten Day Trajectories (combined trajectories)	90
"Spaghetti" Plot with Bottom Topography	106
Acknowledgments	107
References	108

ABSTRACT

This is a final report of SOFAR (Sound Fixing And Ranging) float trajectory data from MODE (Mid-Ocean Dynamics Experiment) for the period September 1972 through June 1976. It begins with a brief historical review and includes a summary of the steps involved in processing the data and computing the trajectories. The data is presented in three ways: 1. Time annotated trajectories on a Mercator projection; 2. Stick plots of float velocity as a function of time; and 3. A sequence of charts, each spanning ten days, showing the spatial relationship and relative motion of all floats. There is also a table of launch, recovery, depth, number of days tracked, average velocity, speed, and kinetic energy for each trajectory.

INTRODUCTION

The concept of using the SOFAR channel to acoustically locate neutrally buoyant floats at great distances was first proposed by Stommel (1949) and later advocated by him in a letter to Deep-Sea Research (1955). His original idea was based on the use of SOFAR DEVICES (a euphemism for explosive) that would be released from a carrier float. For understandable reasons this technology was never developed.

In 1965, a program of development was initiated by Stommel, Webb, Tucker, and Volkmann to evaluate the feasibility of long-range, very low frequency pulsed CW transmission in the ocean (Tucker and Webb, 1970). Encouraging results stimulated the development of a neutrally buoyant SOFAR float (conceptually identical to the Swallow float), which was first used successfully in 1969 in the Bermuda Triangle (Rossby and Webb, 1969; 1971).

Not long after this, Stommel announced plans to organize a synoptic study of ocean currents and their variability in the western North Atlantic. This program later came to be known as MODE. A proposal was submitted to the International Decade of Ocean Exploration Office at the National Science Foundation by Webb and Rossby to develop a new and less expensive type of SOFAR float. From a technological point of view this was a high risk program, since the new float design had not been tested and the timetable had already been prescribed by the field program as a whole. Nevertheless, the proposal was funded and the float design proved to be successful. Twenty floats were built for MODE. The details of the field program, its operation, and some of the data that were collected have been reported in the literature (Rossby, Voorhis and Webb, 1975; Freeland, Rhines and Rossby, 1975) and will not be repeated here.

This document contains plots of all float trajectory data that have been collected between September 1972 and June 1976. In addition to the trajectory plots, the velocity of each float along its path has been computed and plotted as a time series stick plot. A series of ten day charts for the period April 1973 through January 1974, showing the relative motion of all floats as a function of time, is also included. For reference, elementary statistics (i.e., number of days tracked, average speed, velocity, and kinetic energy) are shown in Table 1, but the reader is cautioned that the averages may carry little significance if the trajectory spans different geographical regions which have different energy levels and dynamics. In addition, the depth of each float after launch is given. Due to compressional creep of the main cylinder, floats sink at a rate of 0.85 meters/day (Rossby, Voorhis and Webb, 1975).

SIGNAL TRANSMISSION AND RECEPTION

The MODE experiment was centered at 28°N, 69°40'W. All floats were launched in this area and ballasted for 1500 meters depth (slightly below the sound channel axis). (Figure 1 shows a float being launched from the R/V RESEARCHER). The acoustical signals transmitted by each float radiate horizontally through the ocean at a speed of about 1492 meters/second. Their time of arrival (TOA) at each of several stations yields distances from the float, provided that the transmission time is known. The primary requirement for locating a float is to determine the TOA correctly. This is done by using receivers with a very sharp bandpass filter carefully tuned to the acoustic carrier frequency and by limiting the search for the signal to a narrow window in time centered near the expected TOA.

Four stations have been used in MODE to track the floats. They are located at Bermuda, Eleuthera (Bahamas), Puerto Rico, and Grand Turk. Except for the Bermuda station, all are equipped with digital systems that continuously store the data on computer tape. All stations are equipped with backup systems which record the signals graphically on a drum recorder. The receiver at Grand Turk is shown in Figure 2.

Three acoustic carrier frequencies are employed with up to seven floats operating on each frequency. These floats are identified by their pulse repetition rates (all of which are close to one/minute). In order to make the transmission schedule repeat each day, they are arranged to transmit exactly 1437, 1438, 1439, 1440 (one/minute), 1441, 1442, or 1443 pulses/day. Thus, on a drum revolving one turn/minute, each float has a different slope making it easy to recognize. A sample drum recording with each float TOA labeled is shown in Figure 3. The float, channel, and period information is summarized in Table 2.

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FLOAT STATISTICAL SUMMARY - Table 1

Study	Float	Launch Date	Launch Position	Depth (meters)	Fate	Last Date	Last Position	N	U	V	Speed (cm/sec)	K.E.
2	11	9/28/72	26 39.2N 69 4.6W	1290	F/L	12/25/72	26 15.4N 69 59.6W	86	-1.3	-5	1.9	2.1
3	13	9/28/72	26 39.4N 69 1.5W	1600	R	11/18/72	26 38.5N 69 14.7W	48	-6	-2	2.0	2.5
4	4	11/28/72	27 36.4N 68 22.0W	1490	R	11/23/72	27 37.0N 68 13.6W	0	1.0	0	2.4	3.6
5	4	11/23/72	27 31.8N 68 3.1W	1470	F/L	7/31/73	27 57.7N 66 59.8W	189	0	0	0	0
6	6	11/19/72	27 57.9N 68 .5W	1670	F/L	12/1/72	28 18.3N 67 37.5W	9	3.3	3.8	5.0	12.8
7	12	11/19/72	27 41.1N 68 12.8W	1800	R	11/23/72	27 52.5N 68 2.0W	1	4.9	2.0	5.3	14.0
8	12	11/23/72	28 9.9N 68 3.9W	1510	R	3/17/73	28 11.9N 67 5.9W	102	-1.6	-2	2.2	3.4
9	13	3/9/73	27 42.3N 70 5.5W	1450	F/L	3/18/73	27 34.4N 71 15.5W	19	-1.6	-3	2.8	4.8
10	14	3/10/73	28 40.2N 70 40.0W	1550	R	6/3/73	29 2.5N 70 30.8W	75	2	6	3.9	8.1
11	18	3/10/73	29 7.8N 69 39.5W	1570	R	6/5/73	28 38.5N 69 31.3W	77	4	-1.1	3.3	7.4
12	17	3/11/73	28 43.5N 68 41.2W	1500	F/R	4/10/73	28 12.0N 68 29.8W	0	0	0	0	0
13	19	3/11/73	27 59.9N 69 33.3W	1470	F/R	4/11/73	28 50.5N 70 17.1W	20	-1.9	3.7	4.4	9.8
14	7	3/12/73	26 55.6N 70 12.4W	1600	F/R	3/20/73	26 47.3N 70 10.6W	0	0	0	0	0
15	16	3/12/73	26 59.6N 69 6.9W	1580	F/R	5/10/73	27 5.0N 70 56.5W	42	-8.9	-2	4.4	9.6
16	20	3/12/73	27 45.0N 68 25.1W	1600	R	6/14/73	28 56.0N 69 6.5W	72	-6	2.2	3.2	6.0
17	15	3/20/73	26 47.2N 70 10.6W	1500	F/R	4/14/73	26 22.6N 69 52.9W	20	9	-1.7	2.1	3.5
18	7	3/25/73	28 43.5N 68 32.5W	1550	F/R	4/10/73	28 17.5N 68 35.6W	0	0	0	0	0
19	12	4/7/73	27 43.5N 70 5.1W	1550	F/L	7/18/73	26 38.0N 71 39.0W	98	-1.8	-1.5	3.9	8.7
20	1	4/7/73	28 5.4N 70 9.6W	1540	F/R	7/8/73	27 46.1N 69 28.3W	51	3	-6	3.5	7.4
21	3	4/7/73	28 27.0N 69 49.5W	1540	F/R	4/11/73	28 28.5N 69 48.2W	0	0	0	0	0
22	2	4/8/73	28 24.3N 69 18.1W	1535	F/R	5/4/73	28 24.3N 69 18.1W	21	-1.8	-4.0	4.5	10.5
23	8	4/8/73	27 59.7N 69 37.0W	1520	F/L	4/15/73	27 50.5N 69 46.9W	4	-3.5	-2.9	4.6	10.4
24	5	4/8/73	27 57.3N 69 10.5W	1535	F/R	4/22/73	27 36.4N 69 30.6W	6	-2.4	-3.2	4.0	8.2
25	9	4/10/73	28 12.0N 68 29.6W	1500	F/R	4/22/73	28 19.0N 68 34.7W	2	1	1.1	1.1	6
26	10	4/11/73	28 28.9N 69 50.6W	1555	F/R	4/23/73	28 40.2N 70 .5W	4	-1.7	1.7	2.4	2.9
27	7	4/11/73	26 22.7N 69 53.2W	1550	F/L	6/6/73	25 2.0N 69 45.0W	50	1	-3.1	3.5	6.9
28	15	4/20/73	26 55.1N 68 55.3W	U	F/R	5/4/73	27 9.4N 68 56.9W	0	0	0	0	0
29	19	4/22/73	28 20.3N 68 33.7W	1630	R	6/5/73	28 52.6N 69 16.7W	39	-1.8	1.6	3.1	5.3
30	9	4/22/73	27 36.1N 69 30.0W	1440	R	6/1/73	27 41.5N 70 48.6W	36	-3.6	2	3.7	7.9
31	3	4/23/73	28 36.3N 70 2.4W	1670	F	10/29/73	29 25.3N 73 33.3W	183	-2.0	5	4.7	12.8
32	5	4/24/73	27 33.1N 71 23.9W	1535	R	6/11/73	27 59.7N 71 58.5W	45	-1.3	1.4	2.8	4.3
33	10	5/4/73	27 10.3N 68 55.8W	1530	R	6/10/73	27 4.0N 68 56.9W	34	0	-4	1.6	1.4
34	2	5/30/73	27 56.7N 69 11.2W	1490	R	7/1/73	27 36.4N 69 1.9W	28	7	-1.0	2.1	3.5
35	15	5/31/73	27 33.1N 69 29.3W	1500	F	5/28/74	23 19.4N 72 55.3W	359	-1.1	-1.5	5.3	19.6
36	16	5/31/73	27 33.8N 70 .7W	1500	F	1/17/74	28 27.9N 72 34.5W	223	-1.4	3	4.5	13.1
37	17	5/31/73	28 5.0N 70 10.0W	1500	F	5/25/76	26 8.4N 76 37.8W	1037	-8	-2	5.3	23.1
38	9	6/3/73	29 2.2N 70 30.4W	1555	R	7/4/73	28 6.3N 70 .9W	28	1.6	-4.0	4.4	10.2
39	14	6/5/73	28 39.4N 69 30.9W	1500	F	8/18/75	25 45.9N 74 26.0W	777	-7	-5	5.3	22.1
40	19	6/7/73	27 38.5N 68 41.0W	1500	F	10/31/73	28 8.3N 68 14.6W	143	3	3	1.9	2.3
41	18	6/10/73	27 4.0N 68 56.9W	1500	F	2/10/75	23 38.8N 73 3.1W	519	-8	-9	5.3	21.5
42	10	6/11/73	27 59.2N 71 58.6W	1560	R	6/28/73	27 56.1N 72 28.5W	13	-2.9	-7	3.5	6.3
43	5	6/14/73	28 56.0N 69 6.5W	1500	F	7/31/73	29 8.1N 71 5.5W	44	-4.6	-5	4.8	13.5
44	20	6/18/73	27 8.8N 70 3.6W	1500	F	10/27/74	21 55.2N 70 24.2W	406	-3	-1.4	3.9	10.6
45	10	7/4/73	27 6.3N 70 .9W	1500	S	6/30/76	27 .1N 68 44.9W	1054	1	-2	3.6	8.3
46	2	7/8/73	27 59.8N 69 35.6W	1500	F	11/15/75	21 17.1N 70 6.8W	742	-8	-5	5.9	32.7
47	9	7/8/73	27 14.6N 69 29.9W	1500	F	4/13/74	21 50.4N 71 4.2W	269	-9	-2.4	5.0	17.8
48	1	7/11/73	28 18.0N 68 50.5W	1500	F	6/30/74	23 34.0N 73 7.1W	351	-1.4	-1.7	6.3	26.8
49	4	4/19/74	28 11.4N 69 45.0W	N	S	6/30/76	26 40.1N 64 42.0W	781	7	-3	4.5	13.1

F-Failed, L-Lost, R-Recovered, S-Still signalling, U-Unknown, N-Not applicable

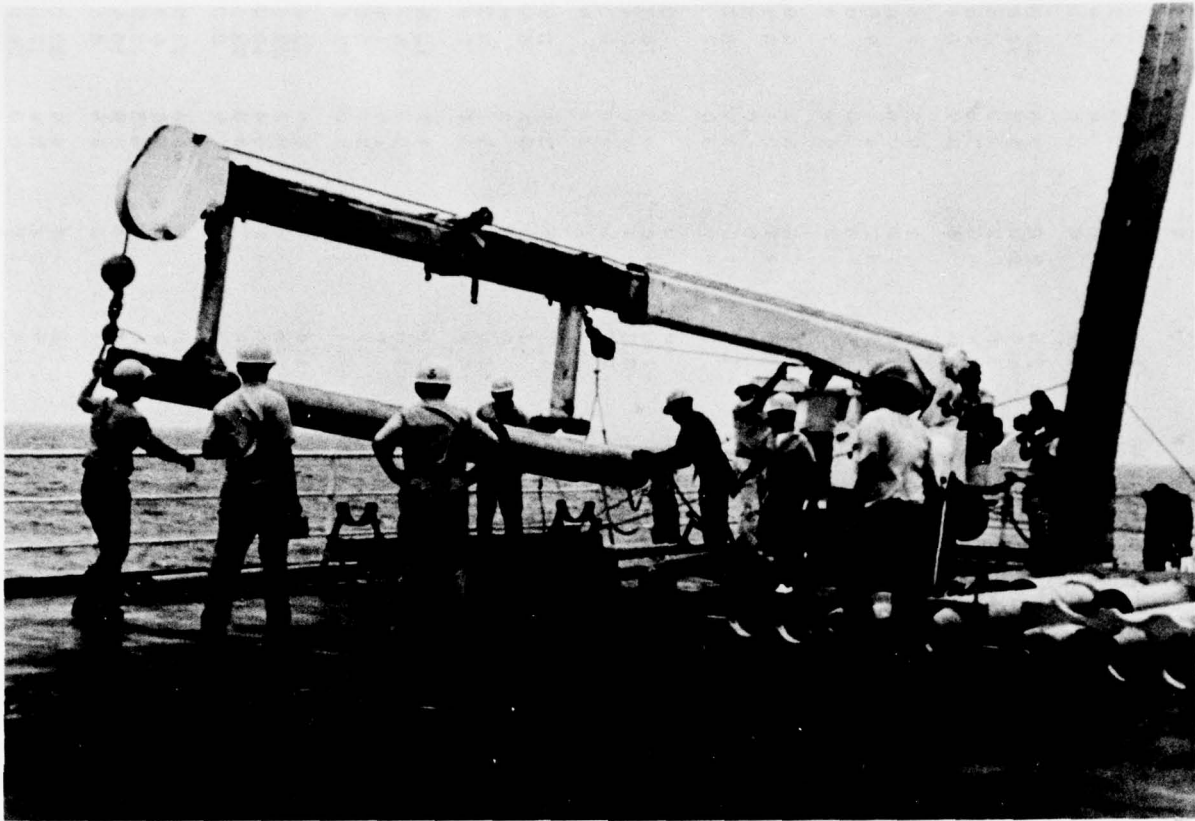


Figure 1 A SOFAR float is being launched from the R/V Researcher. Three other floats are stored on deck for future launches.



Figure 2.

Above:
Listening station at Grand Turk.
Electronic equipment is housed in
the small center shack.



Left:
Grand Turk float signal receiver
and recording equipment.

Photographs by David J. Dorson

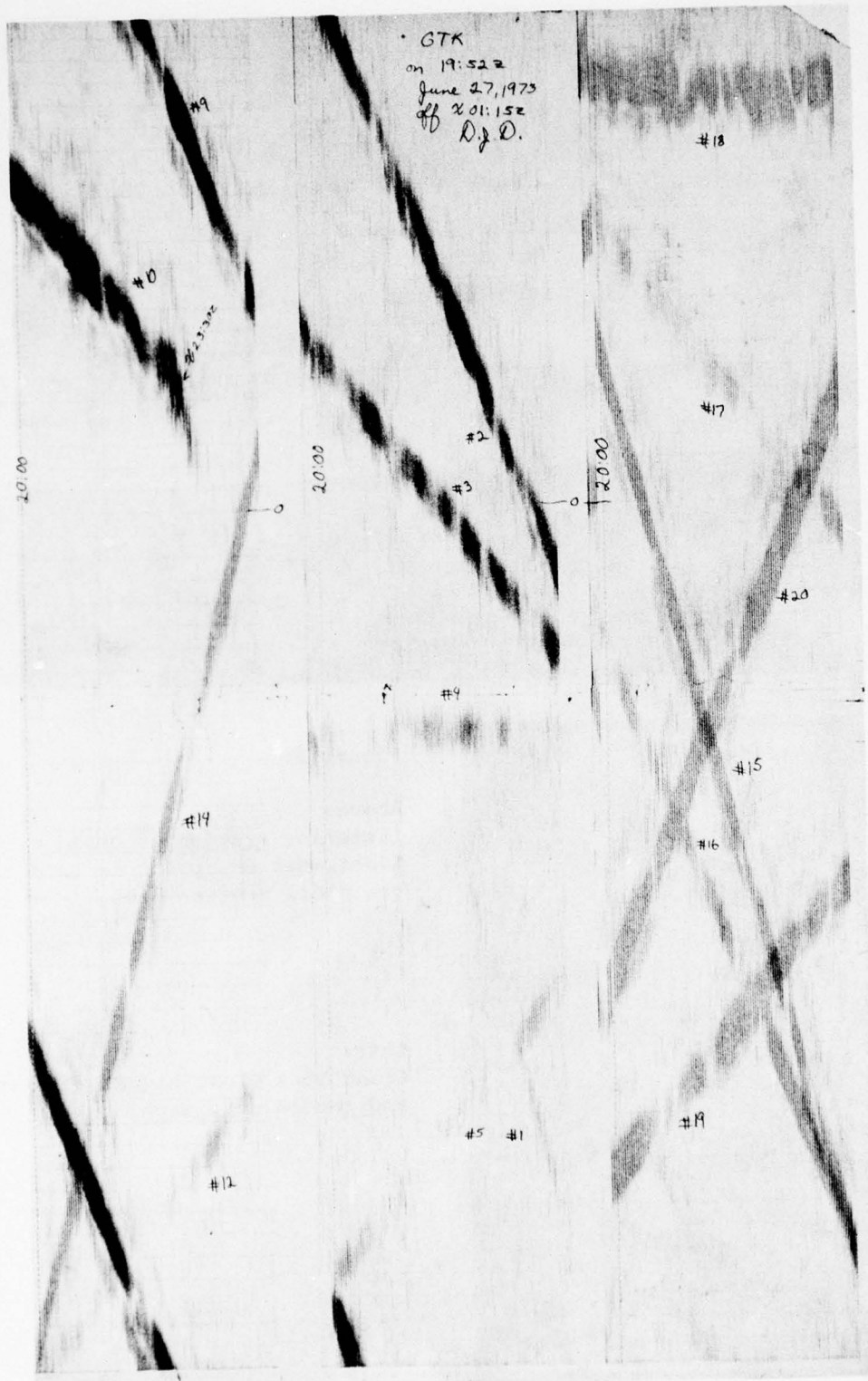


Figure 3

Pulses per day

273.067	1443	1442	1441	1440	1439	1438	1437	
	1	2	3	4	5	6	7	3.6621
270.066	8	9	10	11	12	13	14	3.7028
267.130	15	16	17	18	19	20	21	3.7435
	59.8753	59.9168	59.9584	60.0000	60.0417	60.0834	60.1253	

period (seconds)

7.5	5.0	2.5	0.	2.5	5.0	7.5
---	earlier	---		---	later	---

Change in ATOA (sec/hour)

Channel-Period Table

Table 2

Each receiver consists of a permanently installed hydrophone, at the depth of the SOFAR channel, connected by a shore cable to the amplifiers, filters, and recording equipment. The preamplifiers are very high gain linear systems with high-pass filters near the input to suppress any harmonics (due to non-linearities) that might arise from the energetic low-frequency shipping noises. The output is passed to high-Q filters, which bandpass each of the three carrier frequencies. The 3 dB and equivalent noise bandwidths are 0.7 and 1.2 Hz respectively. After fullwave rectification, the outputs are multiplexed into an analogue to digital converter, which samples and records each channel five times per second as an 11-bit word on a computer compatible seven-track, 556 BPI tape.

DATA PROCESSING PROCEDURES AND PROGRAMS

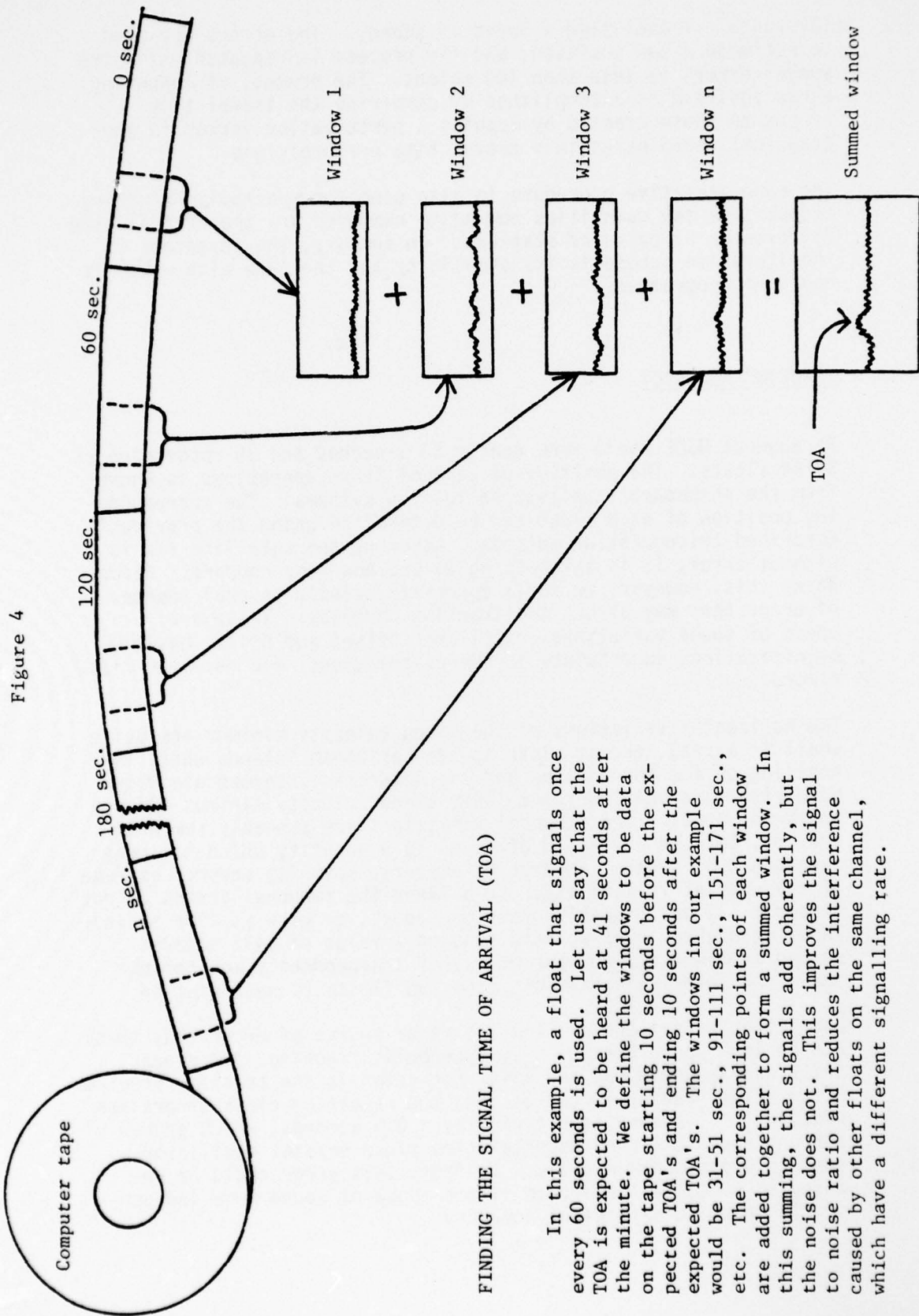
The data processing was done at the Yale Computer Center on the IBM 1401 and 7040-7094 DCS system and, later, on the IBM 370-158. The float tracks were plotted at Yale and the stick plots at the University of Rhode Island on an HP2000 multiprogramming system using a Versatec plotter. The three major computer programs used are: GRIND-tape preprocessor, CRUNCH-TOA finder, and TRACK-float position calculator. The GRIND program was written in ASSEMBLER, and the others were written in FORTRAN IV.

The GRIND program reads the seven-track, 556 BPI tapes mailed from the stations, reformats the data, and writes a nine-track, 1600 BPI tape. Data is checked for correct number of channels, correct order of channels, missing data, data off scale, and irregular station clock increments. Any records having errors are flagged on the output tape and printout.

CRUNCH reads the tape output of GRIND, finds the TOAs for each float, and prints and punches the TOAs. The tape is read, and any data occurring during a float window is added to the summed window for that float (see Figure 4). At the end of a four-hour period of data, the TOAs are found by correlating each summed window with the expected signal shape.

After several weeks of TOAs have accumulated, data is checked by hand. Any datum that is missing, or obviously bad, is replaced by taking data from the backup drum recordings or, when possible, by interpolating data from surrounding good points.

The basic element in the TRACK program is to compute the great circle distance between two points on the Clark spheroid using the Andoyer-Lambert correction (Thomas, 1965). The procedure is iterative. For circular navigation (also known as range-range), a position for the float is assumed and the distances to the receivers computed and then compared to the observed values



FINDING THE SIGNAL TIME OF ARRIVAL (TOA)

In this example, a float that signals once every 60 seconds is used. Let us say that the TOA is expected to be heard at 41 seconds after the minute. We define the windows to be data on the tape starting 10 seconds before the expected TOA's and ending 10 seconds after the expected TOA's. The windows in our example would be 31-51 sec., 91-111 sec., 151-171 sec., etc. The corresponding points of each window are added together to form a summed window. In this summing, the signals add coherently, but the noise does not. This improves the signal to noise ratio and reduces the interference caused by other floats on the same channel, which have a different signalling rate.

(Distance = Travel time x Speed of sound). The errors are used to estimate a new position, and the process is repeated until the sum of errors is less than 100 meters. The process of computing a new position is accomplished by comparing the travel time errors to those created by mapping a perturbation vector in geographical coordinates into travel time perturbations.

The same iterative procedure is also used for hyperbolic tracking except that the quantities now being compared are the arrival time differences at pairs of stations. In summary, the advantage of the iterative scheme is its simplicity and the ease with which it could be programmed.

TRACKING ACCURACY

Throughout MODE there were nearly 50 launches and 35 recoveries of SOFAR floats. The position of each of these operations is known from the shipboard satellite navigation systems. The corresponding position of each float can be determined using the previously described triangulation methods. Assuming the satellite fix is without error, it is interesting to see how they compare. Before doing this, however, we shall summarize briefly several sources of error that may affect the tracking accuracy. These are: speed of sound variations, oscillator offset and drift, baseline magnification, uncertainty in TOA calculations, and receiver clock errors.

The horizontal variations of the sound velocity minimum are quite small ($\pm .2\%$), except close to the Caribbean islands where the shoaling of the thermocline and the Antarctic Intermediate Water give rise to a shallower and lower sound velocity minimum (Rossby and Webb, 1969). The temporal variations are probably somewhat smaller, because the speed of sound is a quantity which has been averaged over several hundred kilometers, spanning several extrema of the spatial variability. We believe the temporal errors do not exceed $\pm .1\%$ and probably occur on "eddy", or weekly, time scales. Thus, throughout MODE we have assumed a value of 1492 meters/second everywhere. We have no way of independently monitoring the sound velocity variations from the floats to each station.

Oscillator offset and drift are a major source of error, but these can be kept under control. By hyperbolic tracking, the clock drift can be monitored and later corrected in the tracking program. After offset and drift correction, the remaining clock errors are usually $< \pm 1$ second, and typically ± 0.5 seconds, which probably reflect speed of sound uncertainties since crystal oscillators tend to drift monotonically. In fact, this error could be reduced to a negligible amount if the speed of sound were independently known to sufficient accuracy.

Baseline magnification errors occur if a float is much farther away from the receivers than the distance separating the receivers, or if the float is close to the baseline between the receivers or an extension of the baseline. Errors magnify as the angle of intersection between the equidistant circles (or correspondingly the hyperbolae) decreases. This is no problem for floats in the MODE area, but is troublesome for floats to the north or west or very close to the Caribbean islands. In addition, several hydrophones can be shadowed from the float by surrounding islands, in which case, there is no way of independently checking the calculations.

There is also uncertainty in calculating the TOAs. One way to obtain an estimate of this uncertainty (or at least a lower bound) is to look at the scatter between two signals which are transmitted with a fixed delay six minutes apart. For strong signals, the standard deviation for this scatter is about 0.25 seconds. If this variance is attributed equally to the main and delay pulse, the standard deviation for a single strong TOA is about 0.2 seconds, which is equivalent to the sampling rate of 5 times/second. As the signal to noise ratio decreases, this jitter increases to 0.6 seconds and more. In this case, it becomes necessary to edit the TOA data sets before they can be used for tracking. One should remember, however, that the above discussion does not include errors due to either speed of sound variations caused by internal waves or changes in the signal shape on time scales longer than six minutes. It is our impression that strong signals (no noise contamination) are relatively unaffected by the complex multipath arrival structure which is so well documented for the classical SOFAR shot. This simply means that most of the "shot" energy is concentrated at the end of the received signal. Thus, from our point of view, the impulse response of the sound channel is nearly an impulse.

Clock errors at the receivers are negligible, since they were frequently checked against WWV.

In summary, for floats in the MODE area, the uncertainties are: $< \pm .1\%$ ($\sim \pm 0.5$ sec.) for the speed of sound, ± 0.5 sec. for the oscillator offset and drift, a small multiplicative factor in the MODE area for baseline magnification, $\pm 0.2 - 0.6$ sec. for TOA calculations, and negligible for the receiver clock errors. The cumulative effect of these is $\leq \pm 1$ second.

Returning to the promised comparisons, we show in Figure 5 the circular float fixes relative to the ship fix for a number of launches. These measurements are the difference between the float's position alongside the ship on the surface, and the first few fixes via underwater sound. These are given for the hydrophone pairs Eleuthera/Grand Turk and Eleuthera/Puerto Rico for clocks that are adjusted hyperbolically immediately after launch, and clocks where no adjustment is made. There is less scatter to the float fixes if the clock is corrected hyperbolically. The overall scatter of the float fixes is about ± 2 km. Bearing

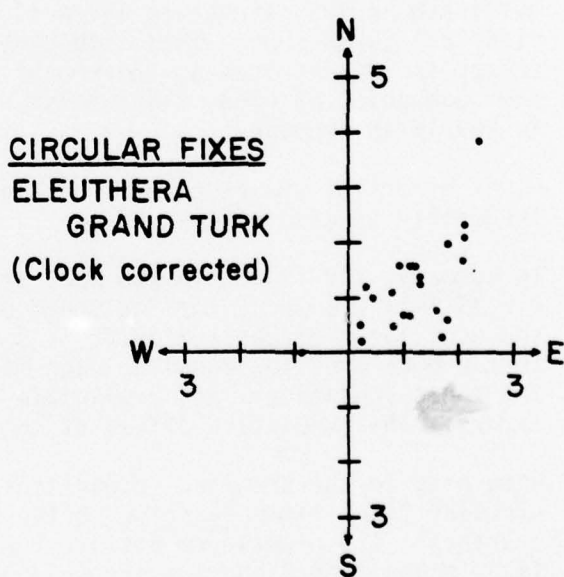
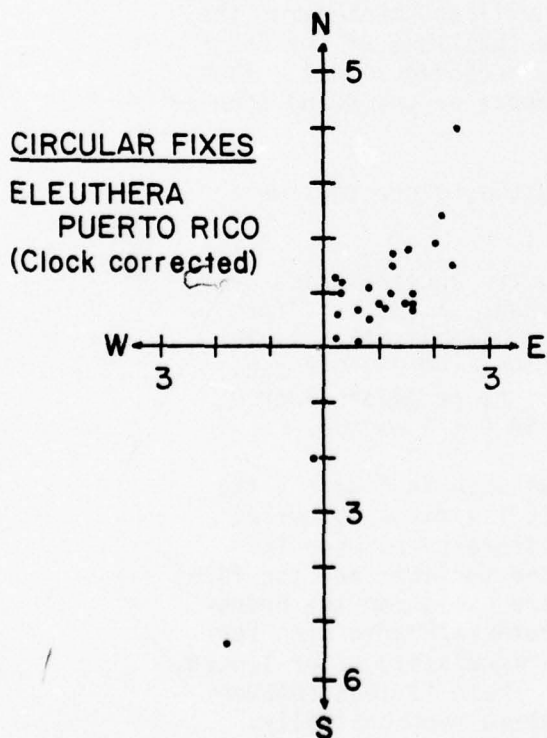
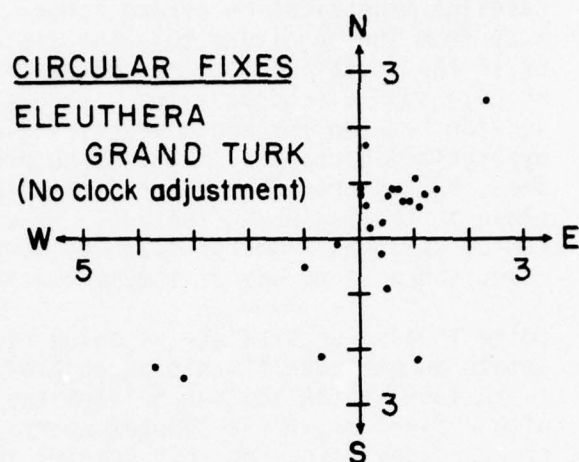
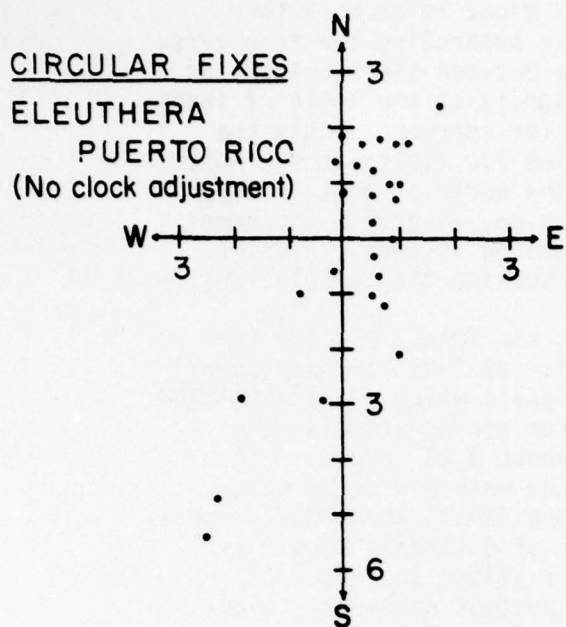


Figure 5

Accuracy of Float Positions (Km)

in mind that each dot is a separate launch at a different time and place, we feel the result is rather good and not inconsistent with the above error discussion. The offset of the float fixes to the northeast relative to the ship is due to the assumption that the speed of sound is 1492 meters/second everywhere. Of course, significant deep motion or shear across the thermocline can introduce additional errors.

CALCULATION OF FLOAT VELOCITIES

The velocity of a float along its track is defined as its rate of change of position as a function of time. Since the individual positions have uncertainties on the order of 1 km, it is not meaningful to compute velocity estimates every few hours. Instead, the time series of position is low pass filtered and subsampled to give velocities once a day.

The procedure is straightforward: given an array of $2N+1$ positions, x_i , as a function of time, t_i , representing either the N/S or E/W coordinate, we calculate the low pass filtered velocity by fitting in a least square sense a parabola, \hat{x}_i , to the array. That is, we define the error function

$$\chi^2 = \sum_{i=-N}^{i=+N} (x_i - \hat{x}_i)^2 = \sum_{i=-N}^{i=+N} (x_i - a - bt_i - ct_i^2)^2$$

and minimize it with respect to a , b , and c , where at $t_0=0$, a , b , and c represent the estimate of position, velocity, and acceleration respectively. It is then possible to solve for the quantities a , b , c using simultaneous equations.

There are two advantages in using this procedure. First, the method does not require equally spaced data (frequently, one or more positions in the series is missing), although a test is made for adequate spread of the data. Second, by simply changing the length of the fit ($2N+1$), we can change the bandwidth of the low pass filter. This is useful when floats undergo rapid velocity changes (see Study 46).

The frequency response of this operation is easily shown. Assuming no missing data, the least squares fit gives the velocity estimate $b = \sum t_i x_i / \sum t_i^2$, where the sum is from $-N$ to $+N$. Since this is an antisymmetric function, let $x_i = A \sin \omega t_i$ where ω is the frequency.

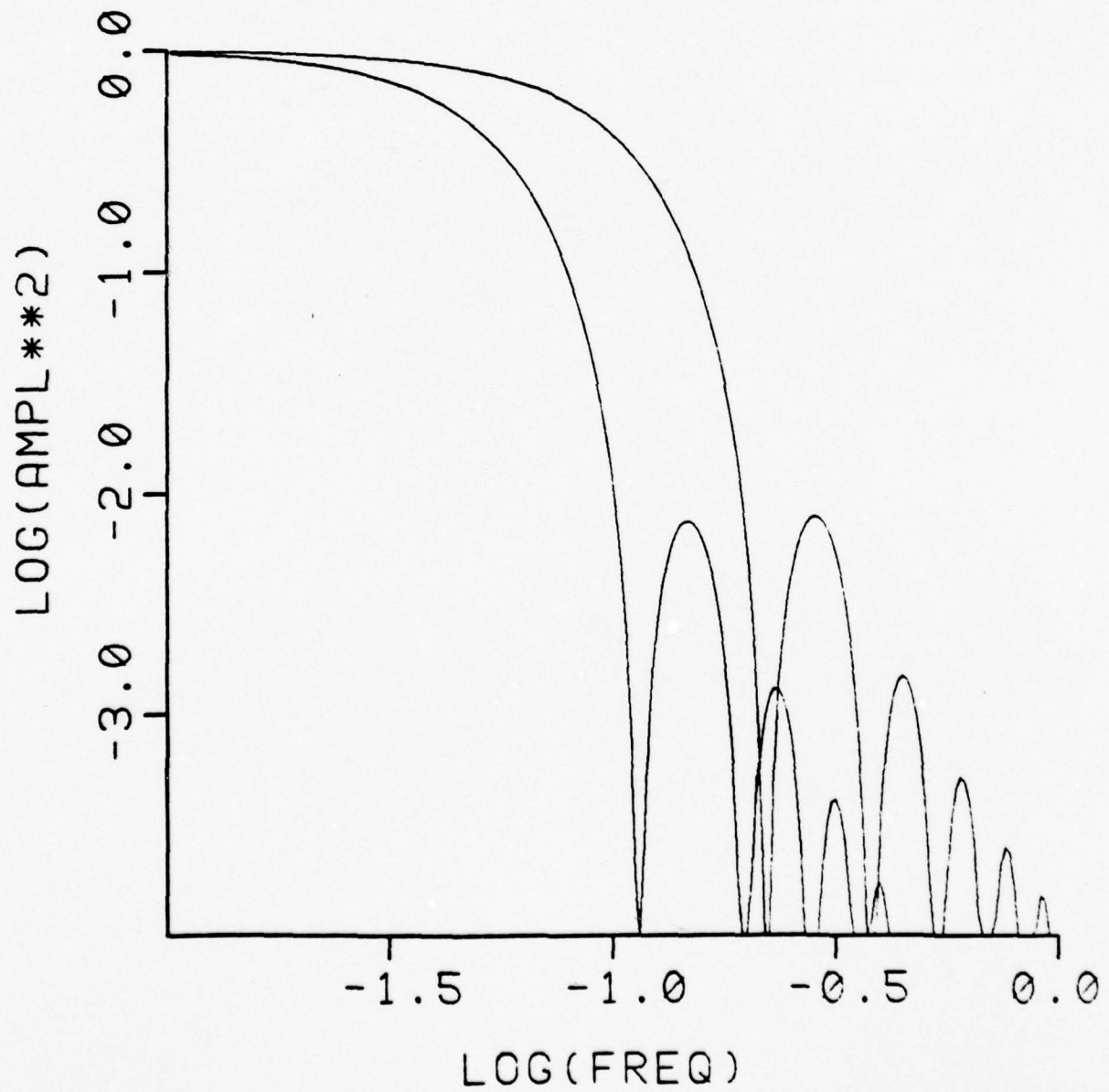
By writing $\omega = \frac{2\pi}{2\Delta t} \omega'$ where $2\pi/2\Delta t$ is the Nyquist frequency, and $t_i = i\Delta t$, we obtain $b = A \sum i \sin(\omega' \pi i) / \Delta t \sum i^2$. Thus,

$b^* = \sum i \sin(\omega' \pi i) / \sum i^2$ becomes the attenuation coefficient for the velocity in dimensional units given by A and Δt as a function of frequency.

The non-dimensional frequency response of this differentiating low pass filter, $(b^*)^2$, is shown in Figure 6 for the cases, $N=6$ and $N=12$. In computing the velocity stick plots in this report we used $N=11$, which gives a 1/2 power cutoff at a period corresponding to $\sim 5 \frac{1}{2}$ days.

Figure 6

Frequency Response of Low Passed Differentiator

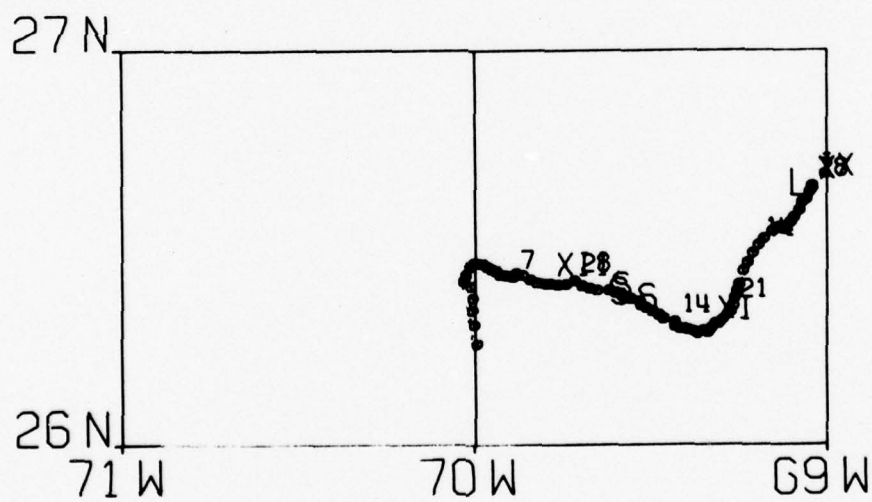
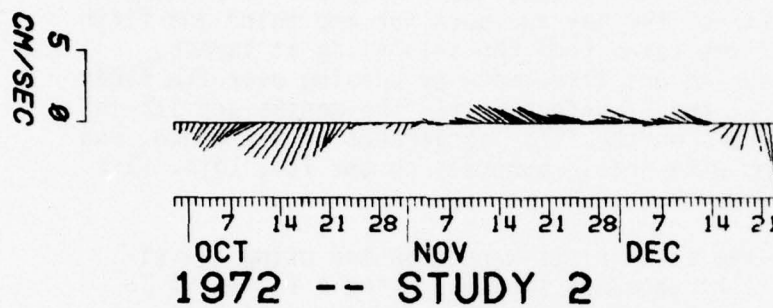


TRAJECTORIES AND STICK PLOTS

Trajectories and stick plots for each float are identified by study number since many of the floats were launched more than once. The scale for the trajectories is two inches per degree of longitude for most studies, but studies 37, 39, 41, 46, 48, and 49 are plotted one inch per degree of longitude. No smoothing is done on the data, and three positions per day are plotted on a Mercator projection. A symbol is plotted for the first fix of the day and dots for the third and fifth fixes. Float fixes taken from the ship's log at launch, recovery, and subsequent fixes made by passing over the float are labeled L, R, and S respectively. The months are labeled with Roman numerals on the first occurrence of the month, and days are labeled with Arabic numerals on the 7th, 14th, 21st, and 28th of the month.

Velocities for the stick plots were computed using all six fixes per day. The data was smoothed using a filter of 23 points, so any studies with less than four days of data are omitted. A time scale with month and day labels is given below the plot and a speed scale of centimeters/sec. is on the side.

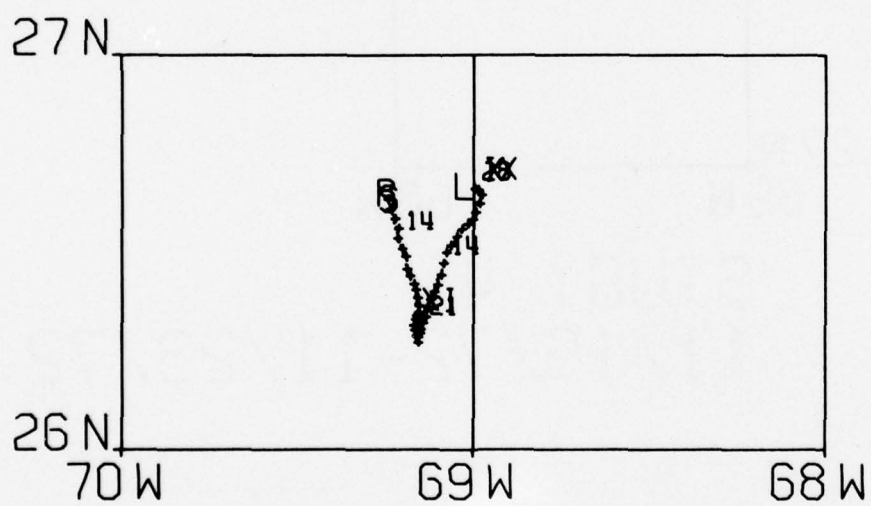
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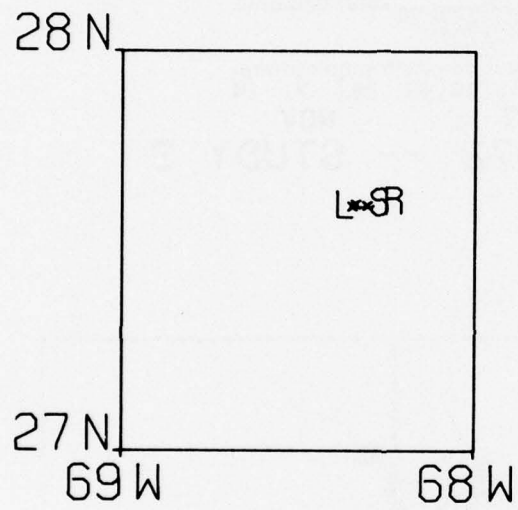


STUDY 2
9/28/72-12/25/72

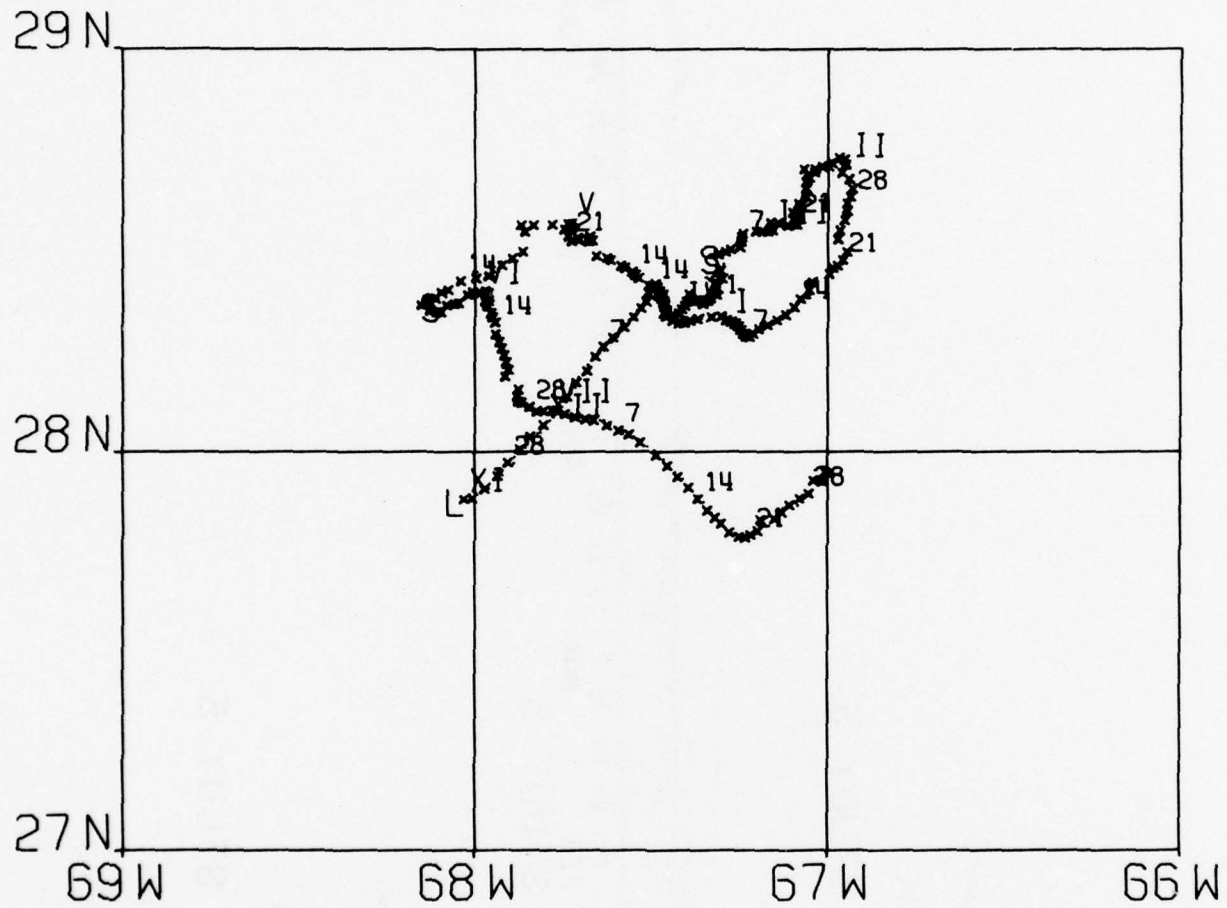
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CM/SEC7 14 21 28 7 14
OCT NOV

1972 -- STUDY 3

STUDY 3
9/28/72-11/18/72



STUDY 4
11/19/72-11/23/72



STUDY 5

11/23/72-7/31/73

5 0
CM/SEC



28 7 14 21 28

DEC

1972 -- STUDY 5

5 0
CM/SEC



28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28

JAN

FEB

MAR

APR

MAY

JUN

1973 -- STUDY 5

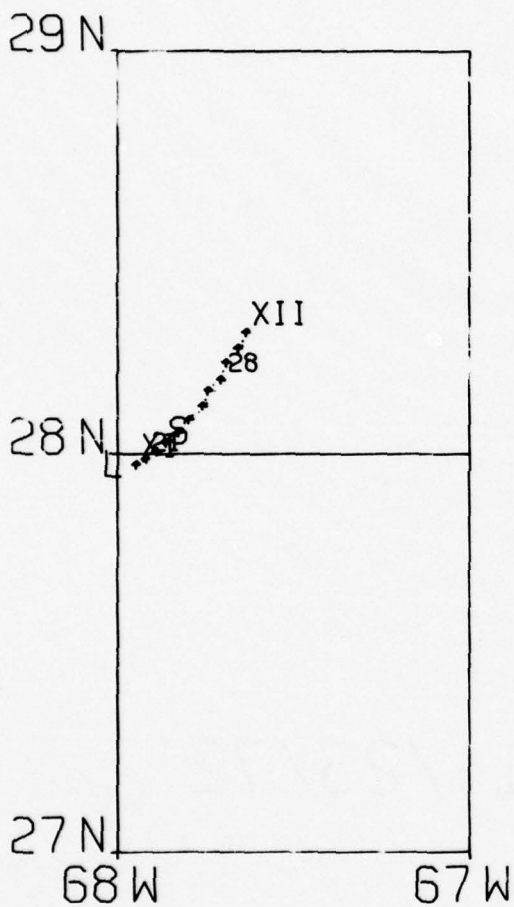
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CM/SEC



28 7 14 21 28

JUL

1973 -- STUDY 5

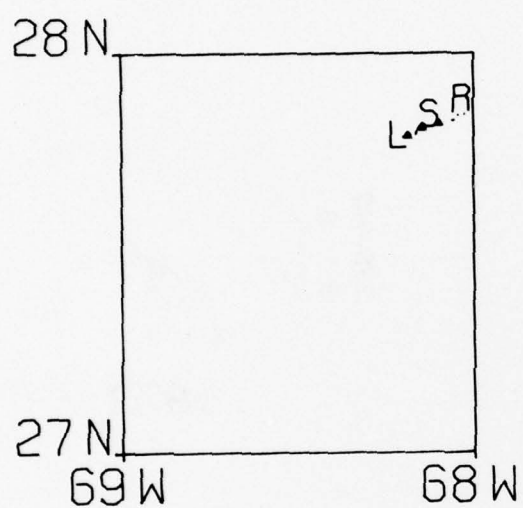


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CM/SEC



1972 -- STUDY 6

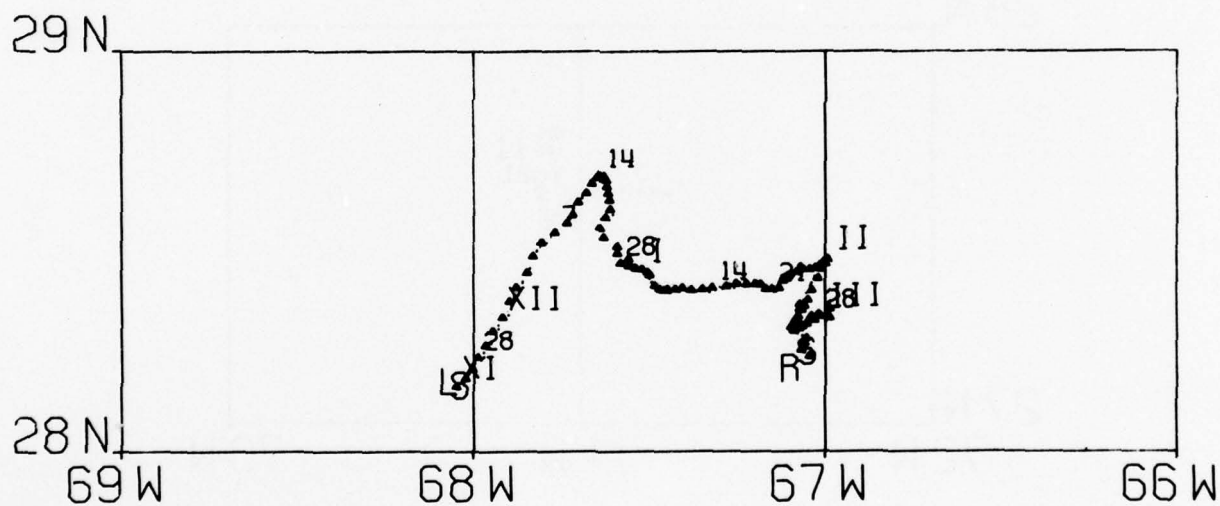
STUDY 6
11/19/72-12/1/72



STUDY 7
11/19/72-11/23/72



28 7 14 21 28 7 14 21 28 7 14 21 28 7
DEC JAN FEB MAR
1972 -- STUDY 8



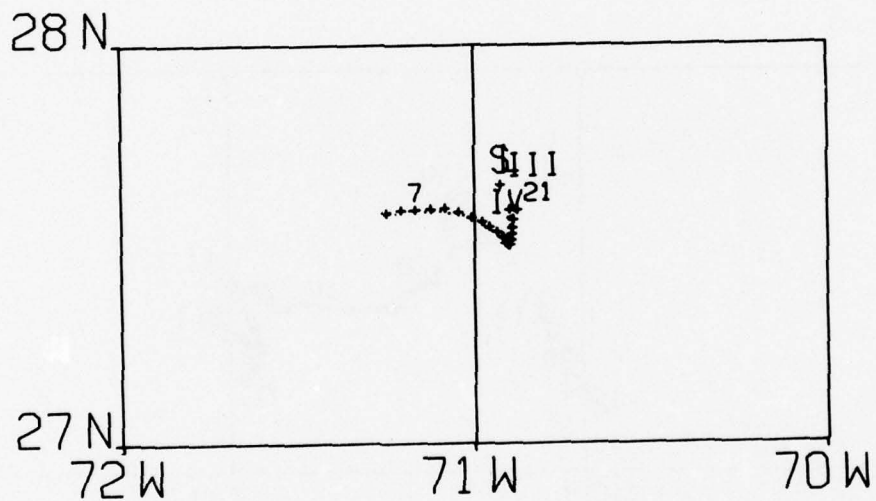
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11/24/72-3/17/73

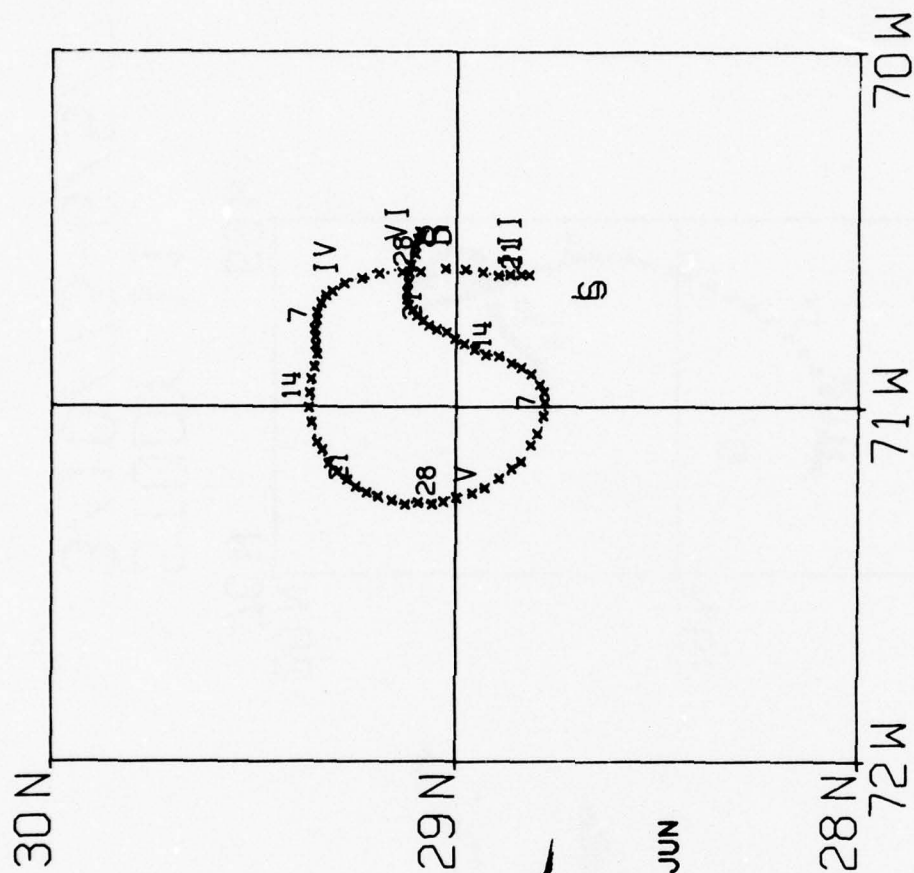
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CM/SEC

21 28

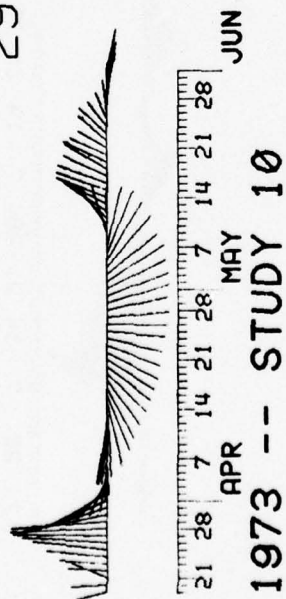
APR

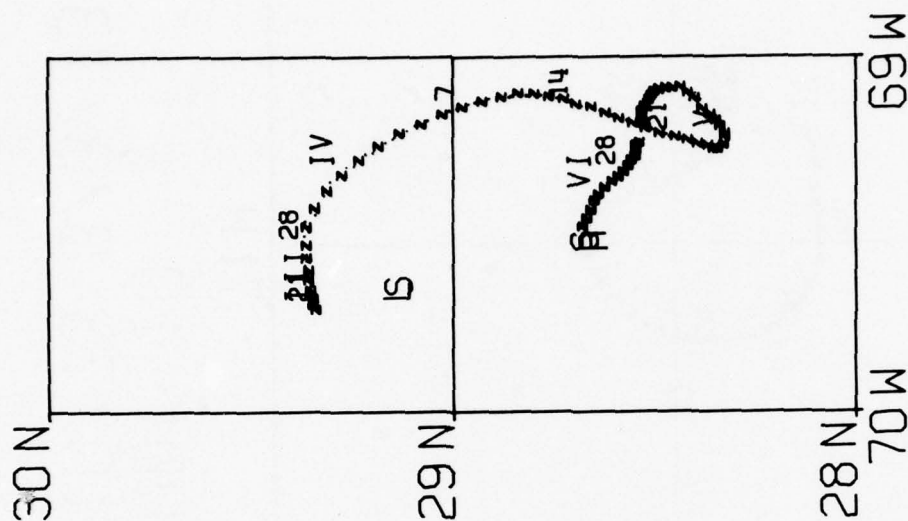
1973 -- STUDY 9

STUDY 9
3/9/73-4/8/73



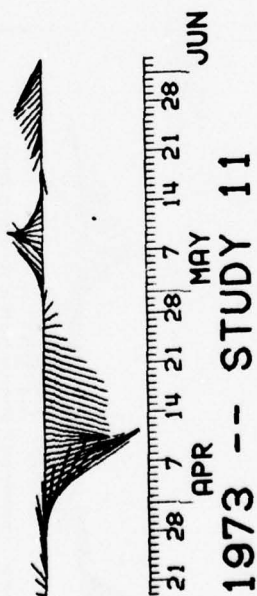
STUDY 10
3/10/73-6/3/73

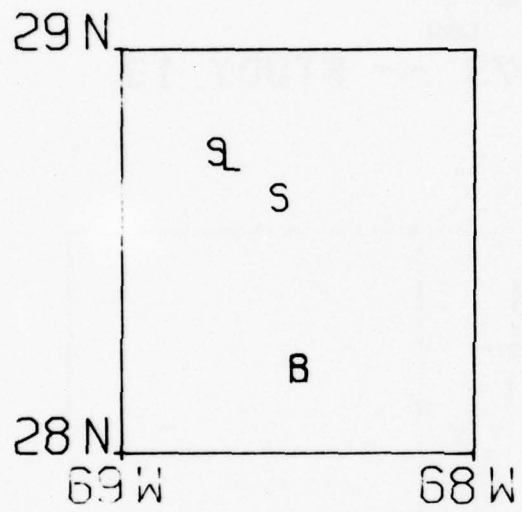




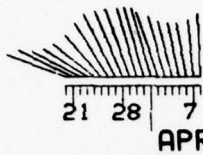
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CM/SEC

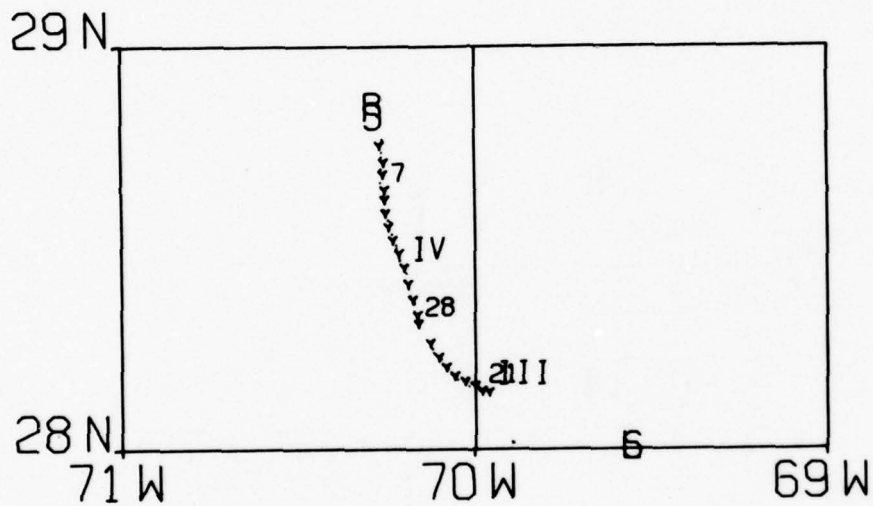


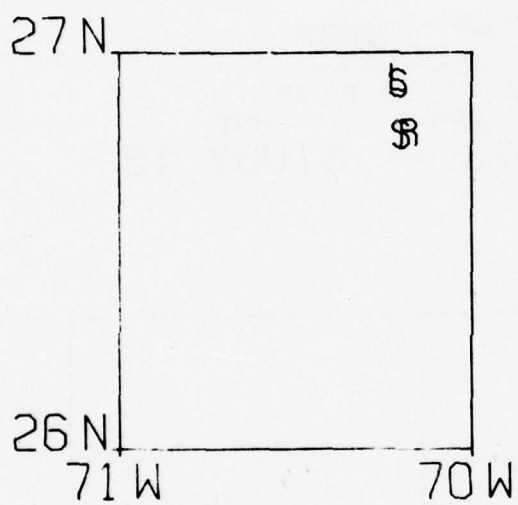


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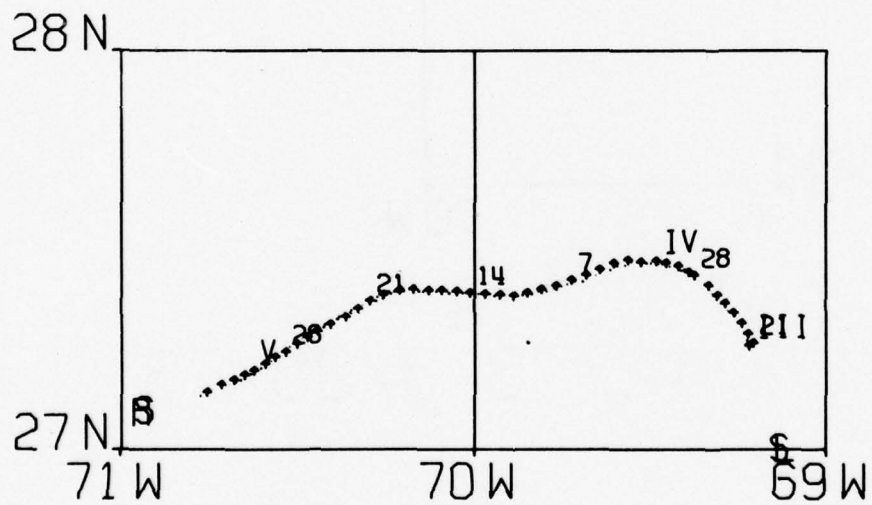
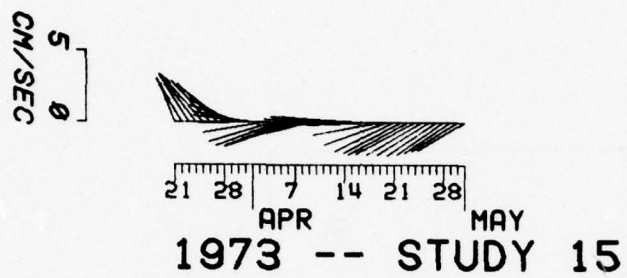
CM/SEC
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1973 -- STUDY 13

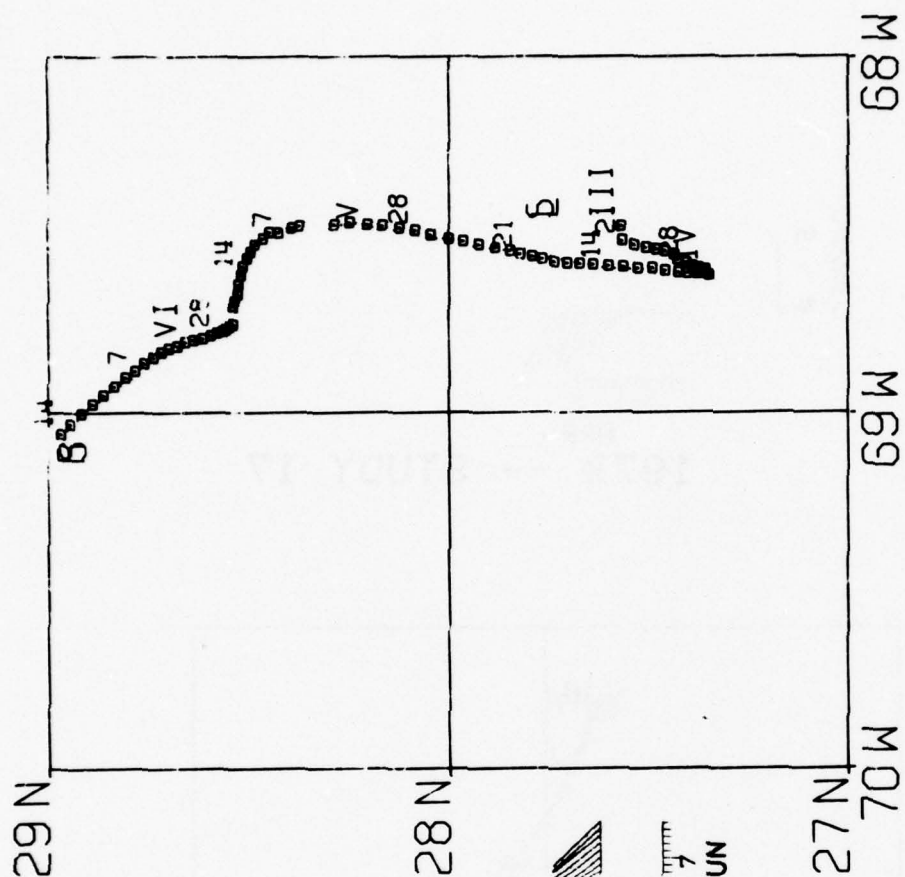
STUDY 13
3/11/73-4/11/73



STUDY 14
3/12/73-3/20/73



STUDY 15
3/12/73-5/10/73



STUDY 16
3/12/73-6/14/73



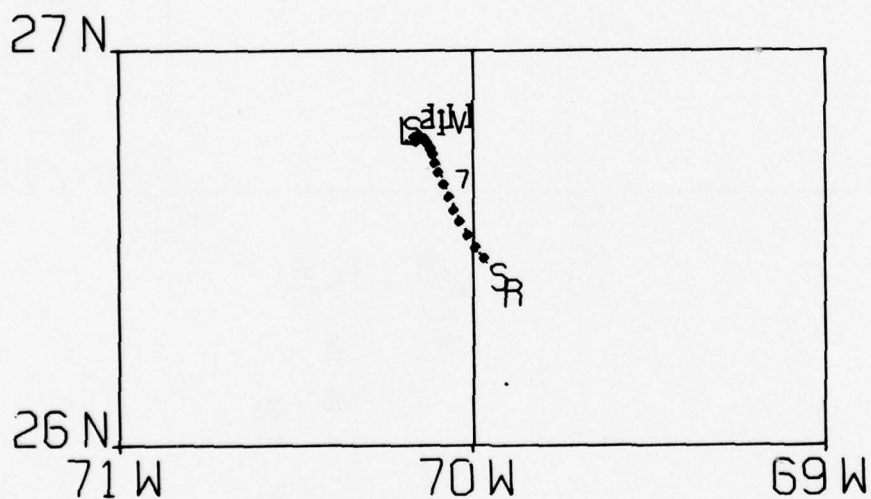
21 28 7 14 21 28 7 14 21 28 7 JUN
APR MAY 1973 -- STUDY 16

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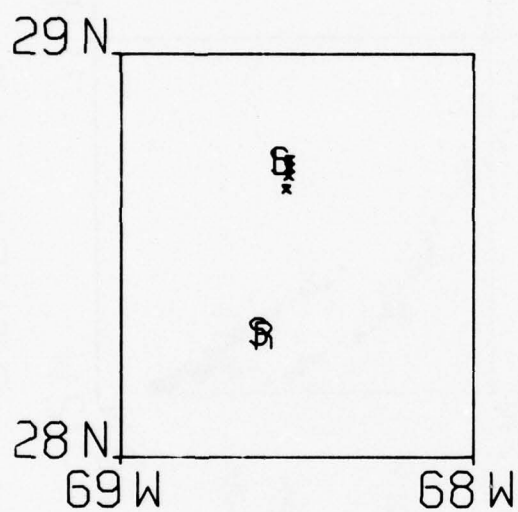


28 7
APR

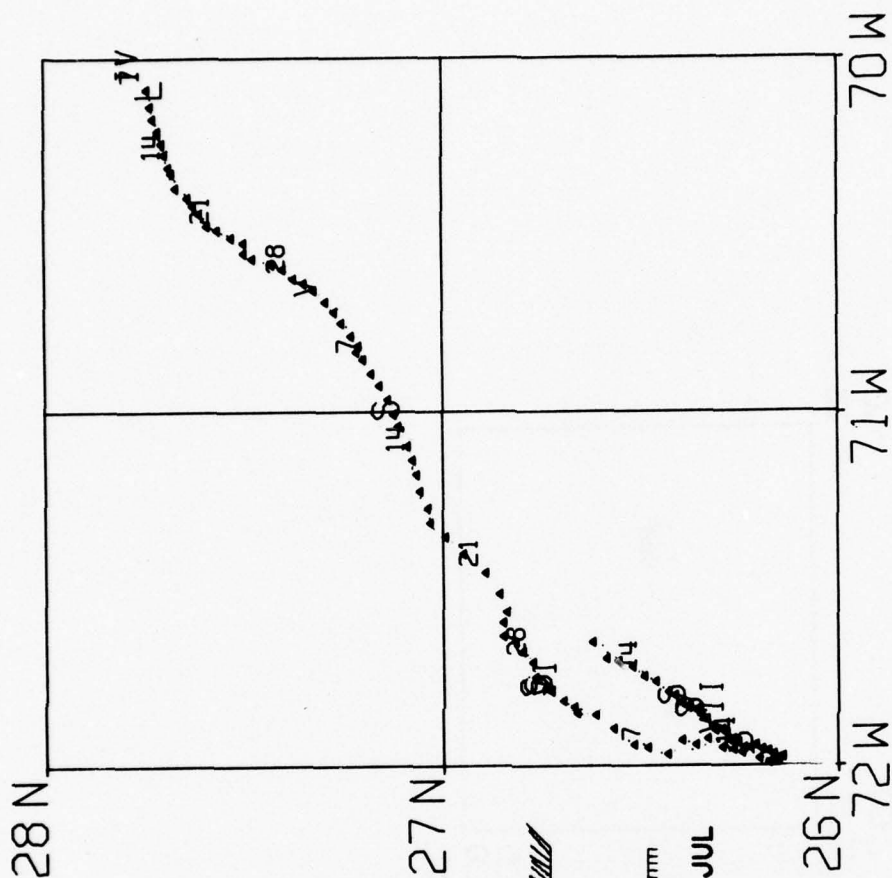
1973 -- STUDY 17



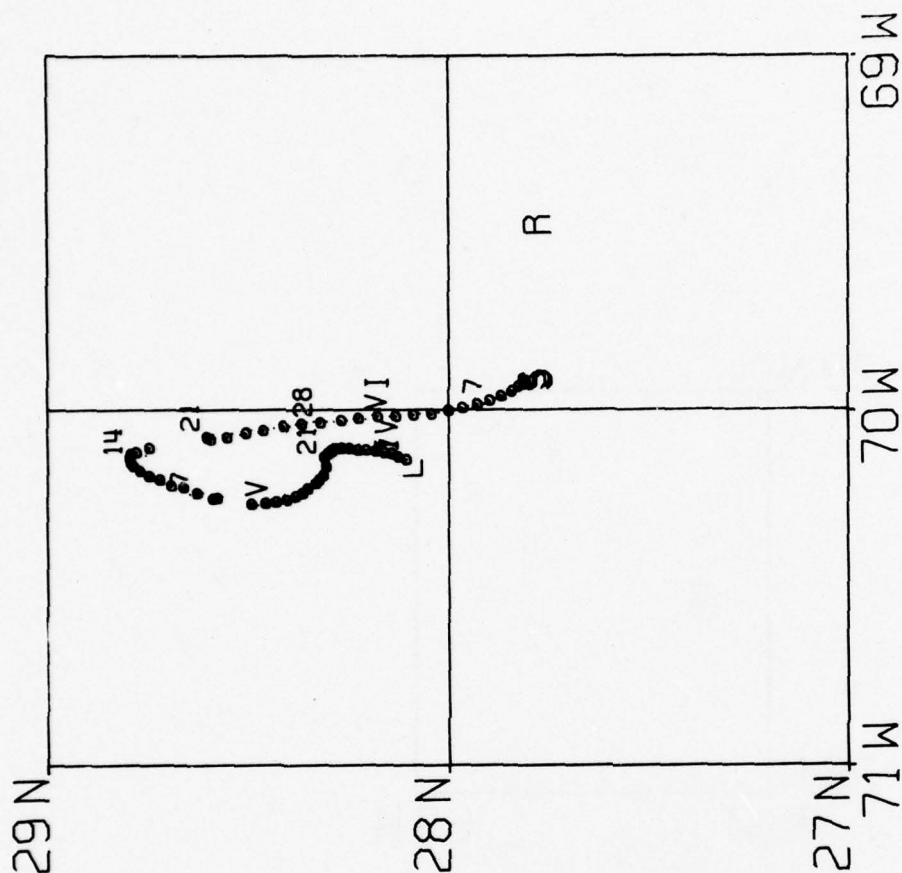
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3/20/73-4/14/73



STUDY 18
3/25/73-4/10/73

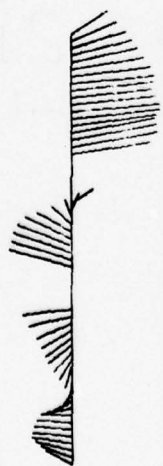


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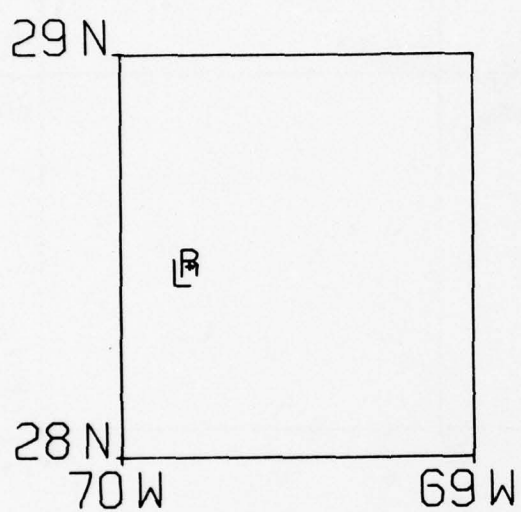


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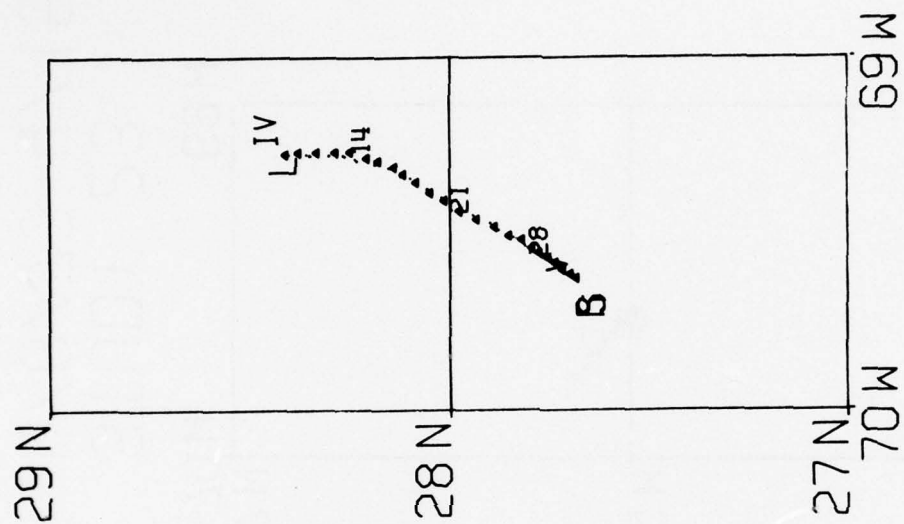
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CM/SEC



14 21 28 7
APR MAY JUN
1973 -- STUDY 20



STUDY 21
4/7/73-4/11/73

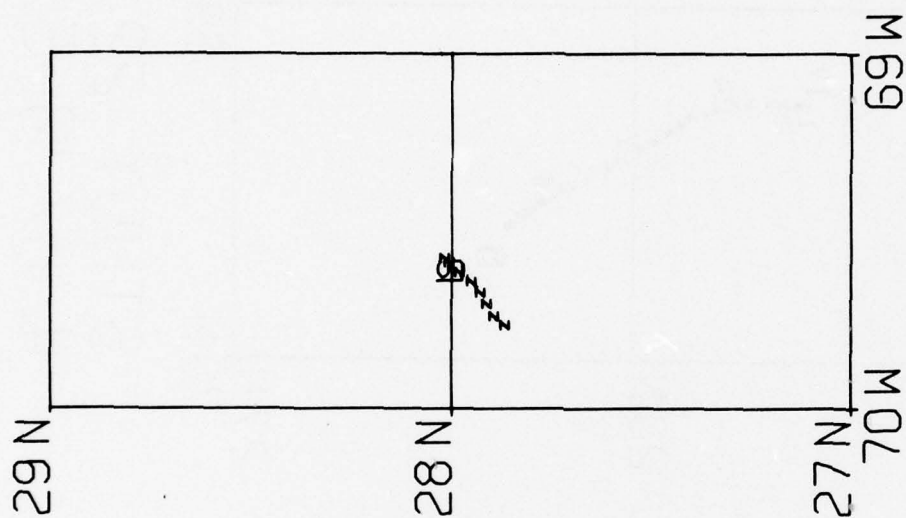


STUDY 22
4/8/73-5/4/73

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CM/SEC



APR 1973 -- STUDY 22



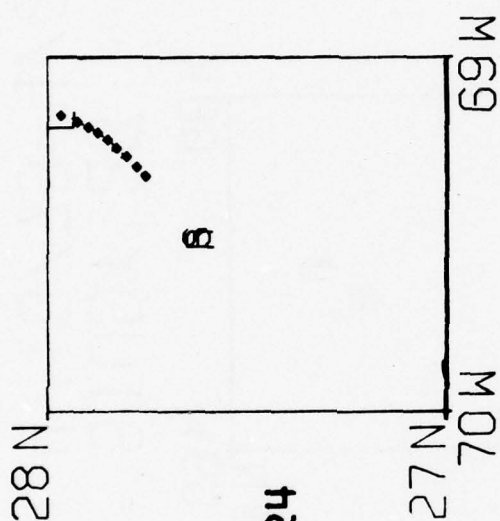
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4/8/73-4/15/73

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CM/SEC



APR

1973 -- STUDY 23



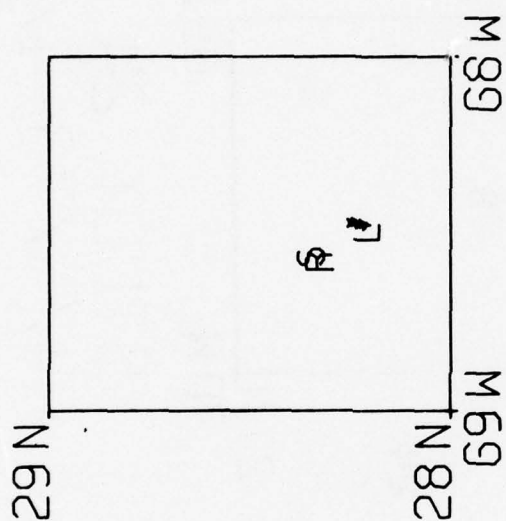
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CM/SEC



14
APR

1973 -- STUDY 24

STUDY 24
4/8/73-4/22/73

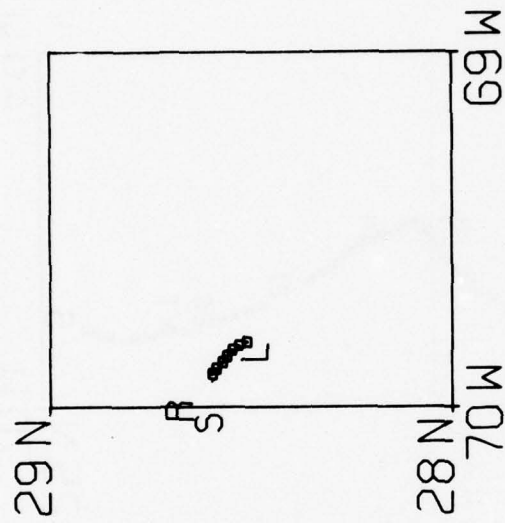


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CM/SEC

APR
1973

-- STUDY 25

STUDY 25
4/10/73-4/22/73

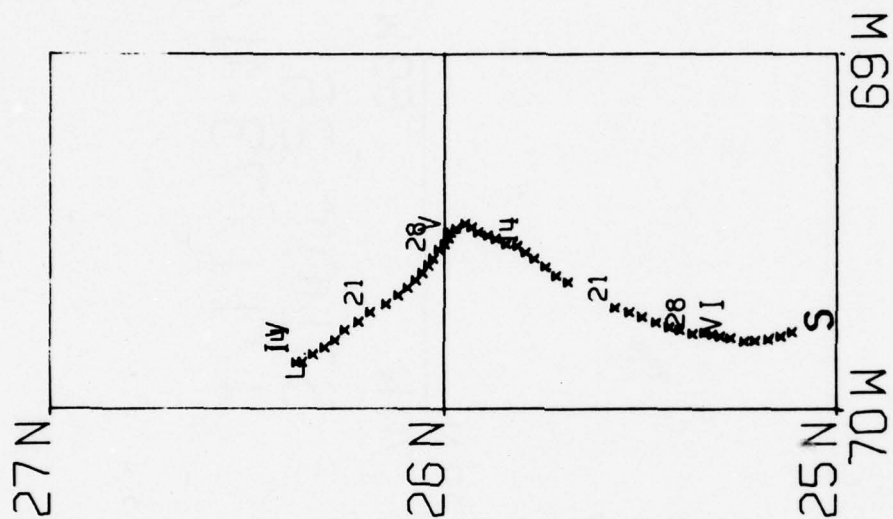


STUDY 26
4/11/73-4/23/73

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CM/SEC

APR 1973

-- STUDY 26

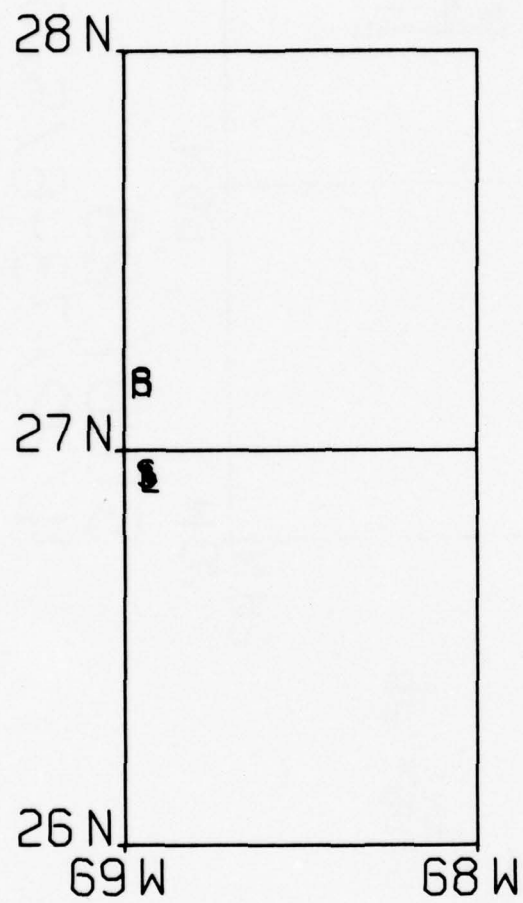


STUDY 27
4/14/73-6/6/73

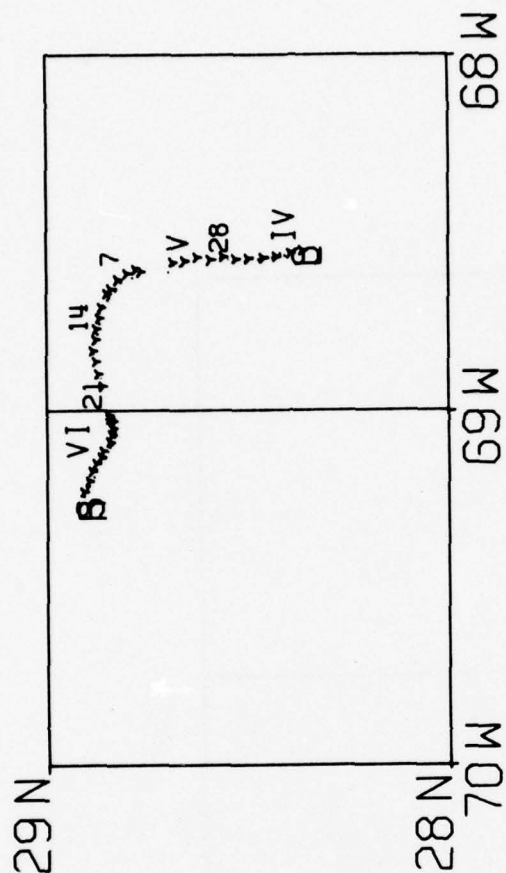
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CM/SEC



21 28 7 14 21 28
MAY JUN
1973 -- STUDY 27



STUDY 28
4/20/73-5/4/73

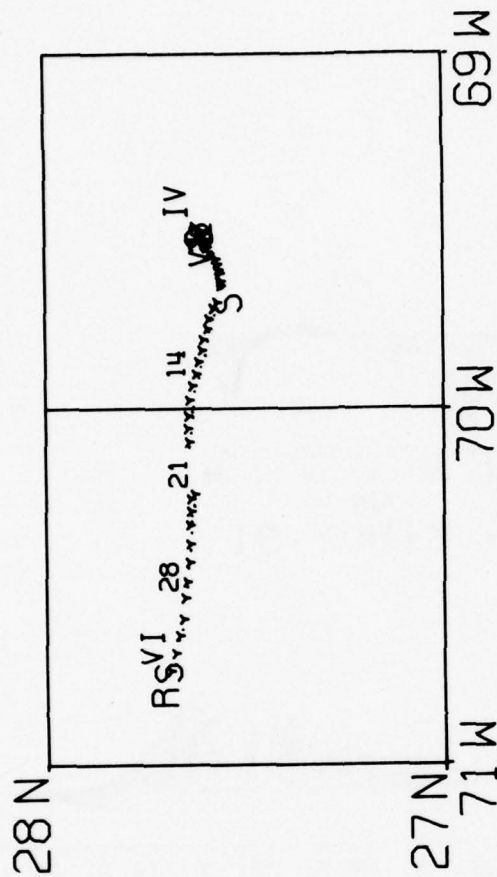


STUDY 29
4/22/73-6/5/73

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CM/SEC



1973 -- STUDY 29
MAY JUN



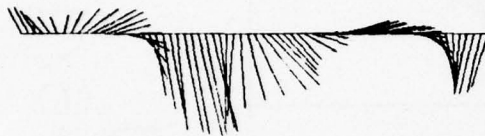
STUDY 30
4/22/73-6/1/73

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CM/SEC



MAY
1973 -- STUDY 30

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CM/SEC

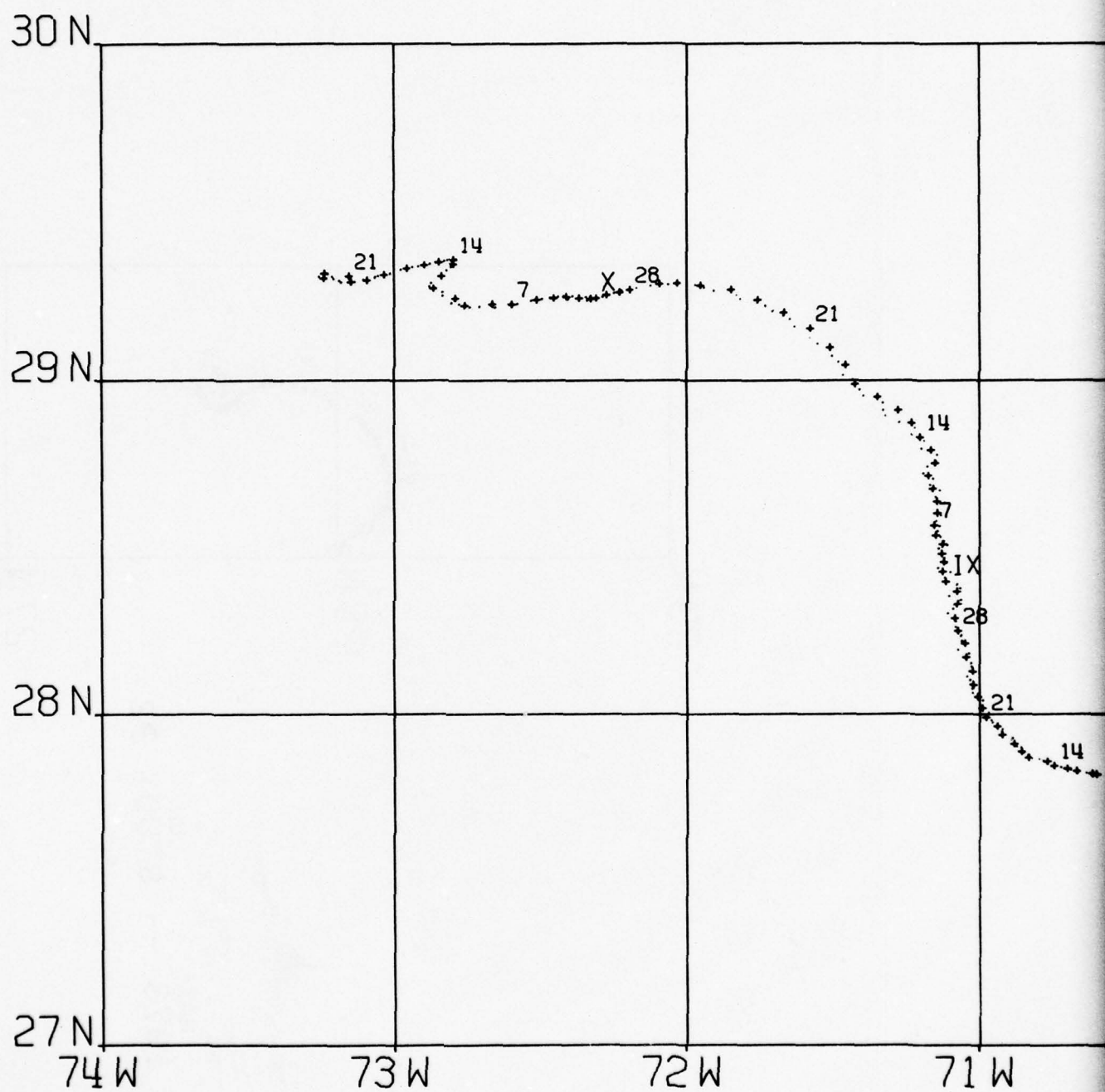


28 7 14 21 28 7 14 21 28
MAY JUN
1973 -- STUDY 31

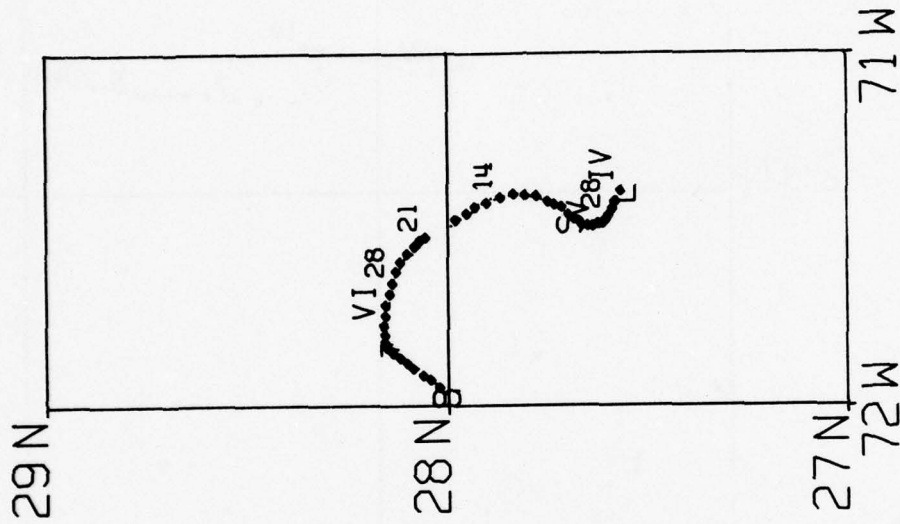
10
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7 14 21 28 7 14 21 28 7 14 21 28 7 14 21
JUL AUG SEP OCT
1973 -- STUDY 31



STUDY 31
4/22/73-10/29/73



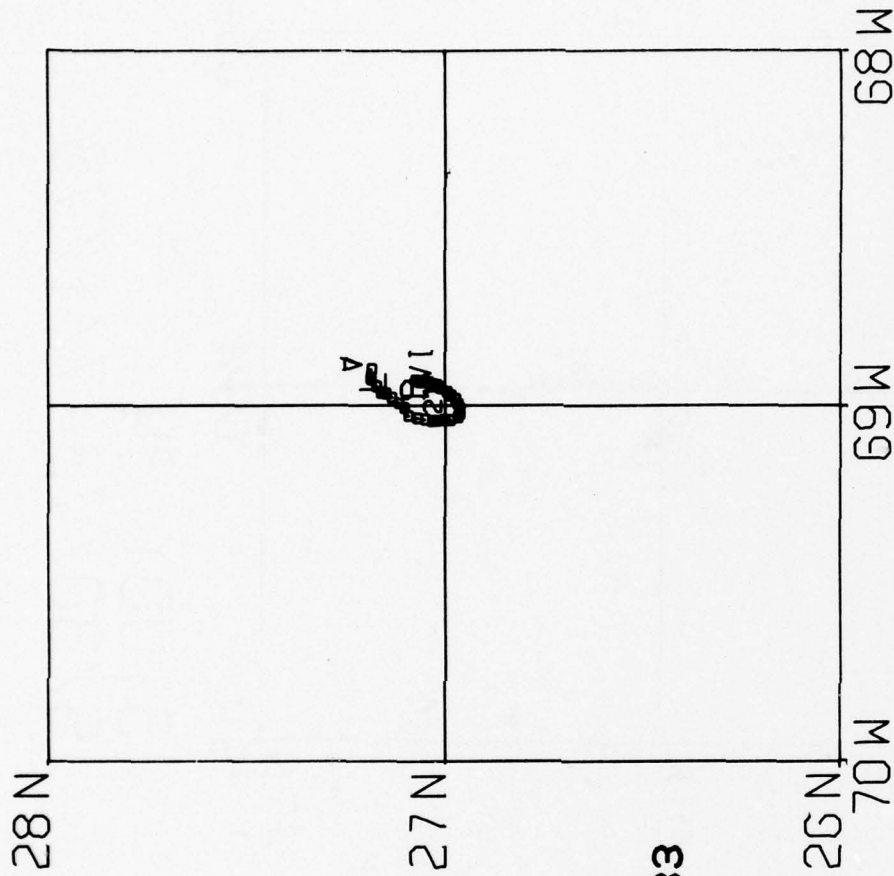
STUDY 32
4/24/73-6/11/73

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CM/SEC



28 14 7 0
MAY JUN

1973 -- STUDY 32



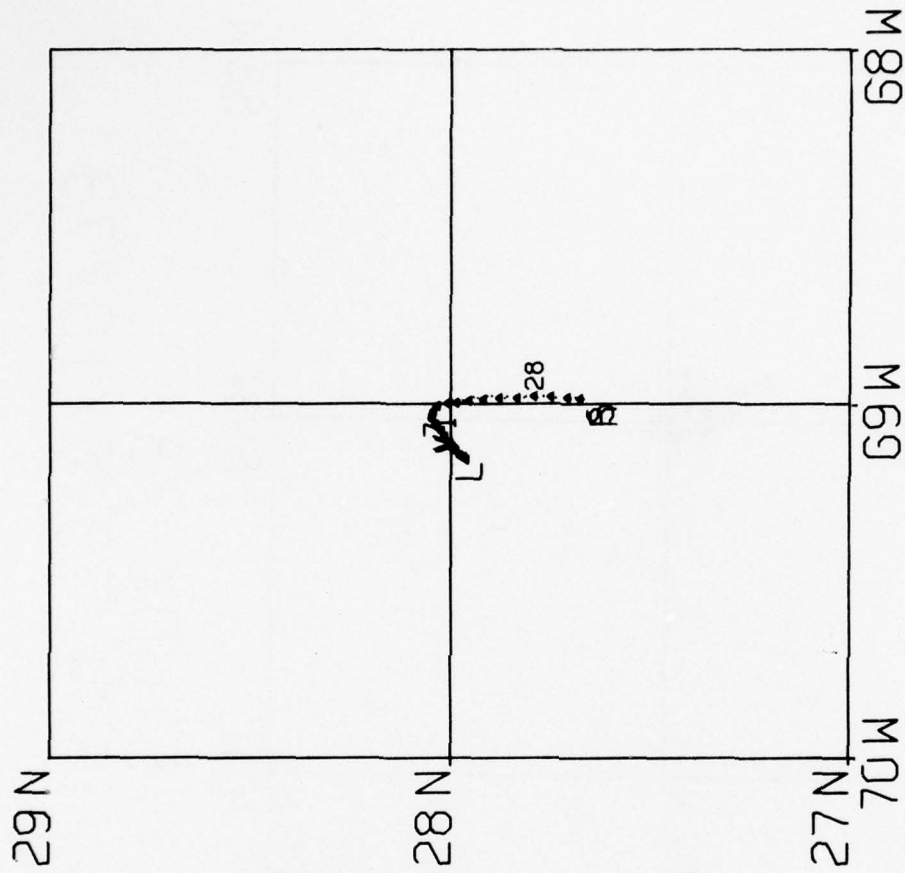
STUDY 33
5/4/73-6/10/73

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CM/SEC



MAY 14 21 28 JUN 7

1973 -- STUDY 33



STUDY 34
5/30/73-7/1/73



1973 -- STUDY 34

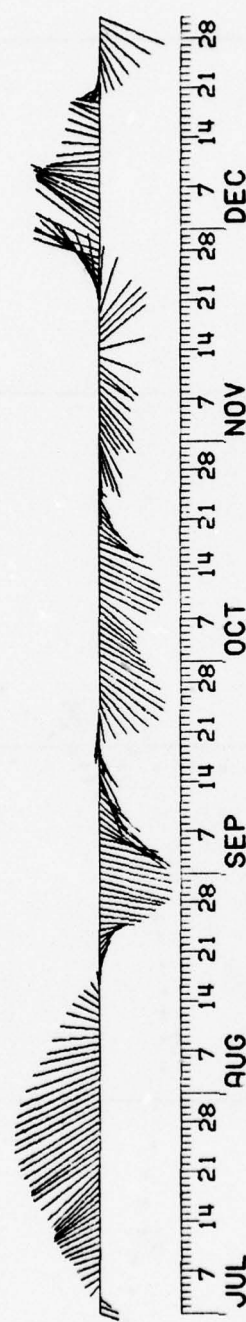
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CM/SEC



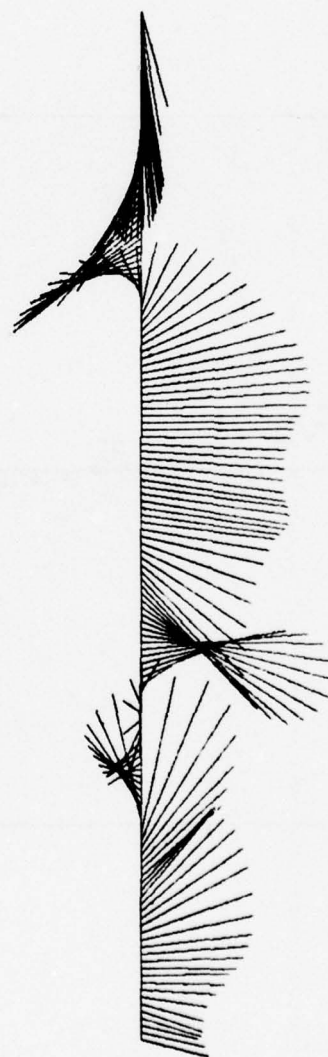
JUN
1973 -- STUDY 35

10 5 0
CM/SEC



JUL
1973 -- STUDY 35

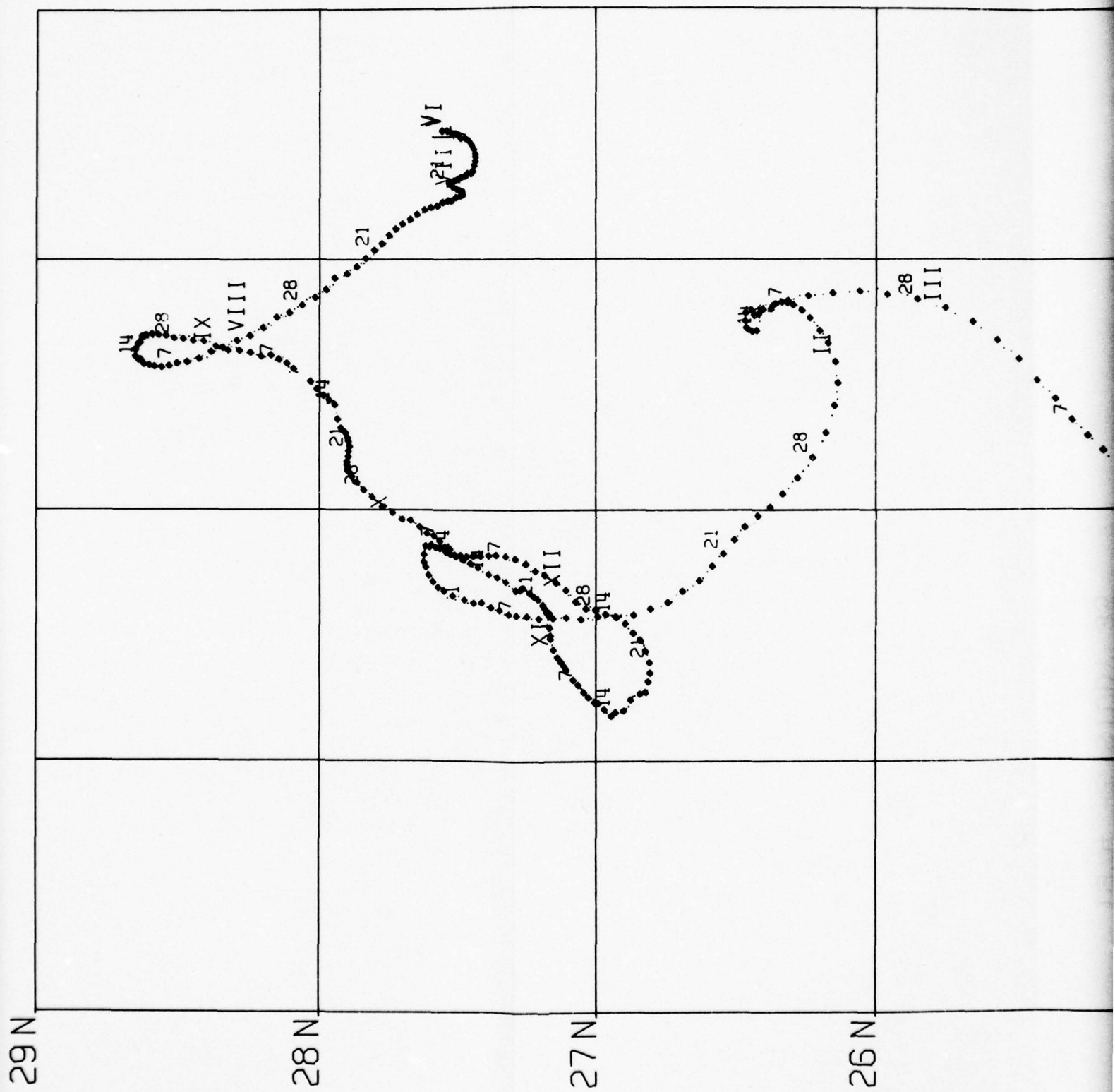
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CM/SEC

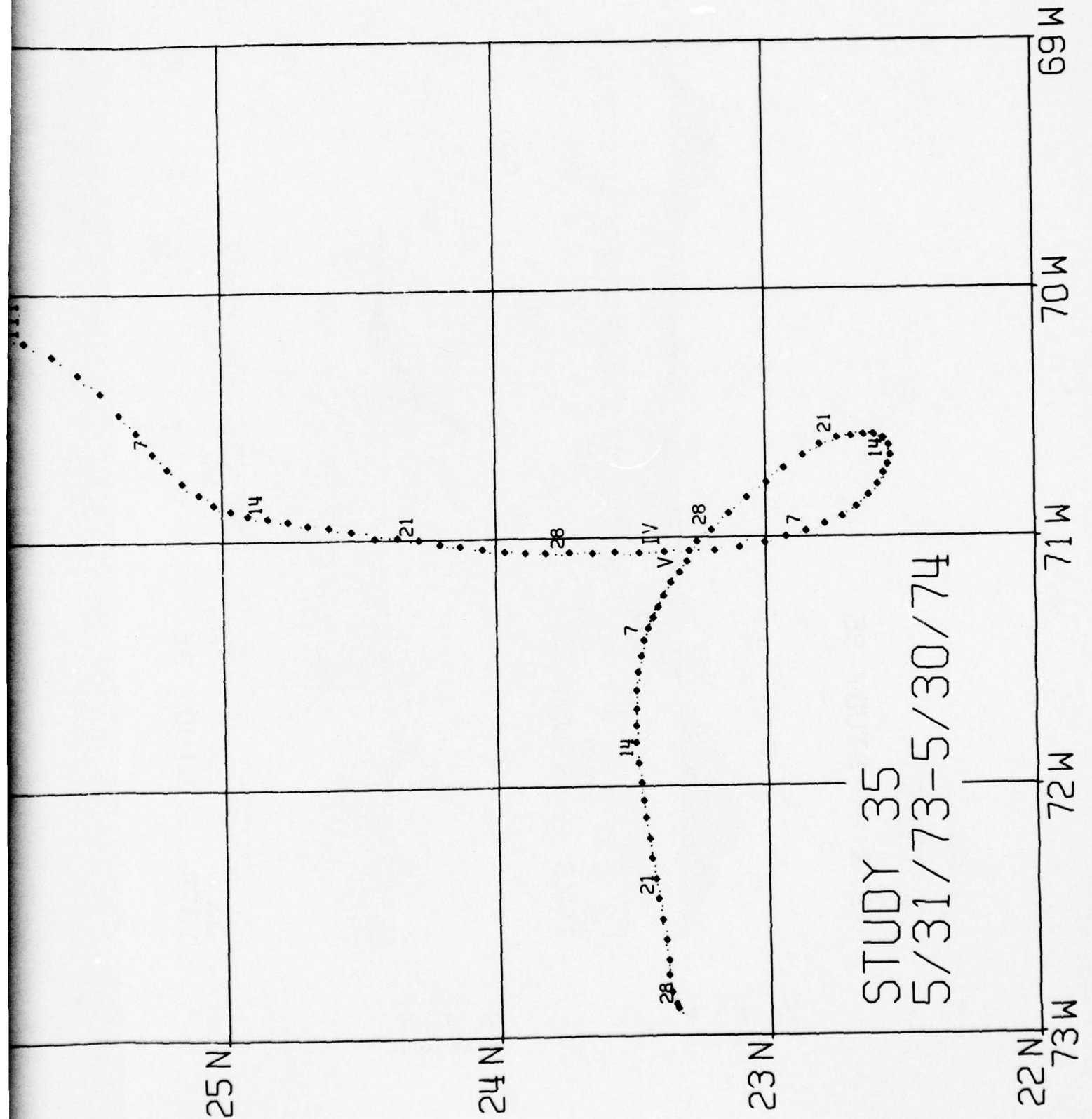


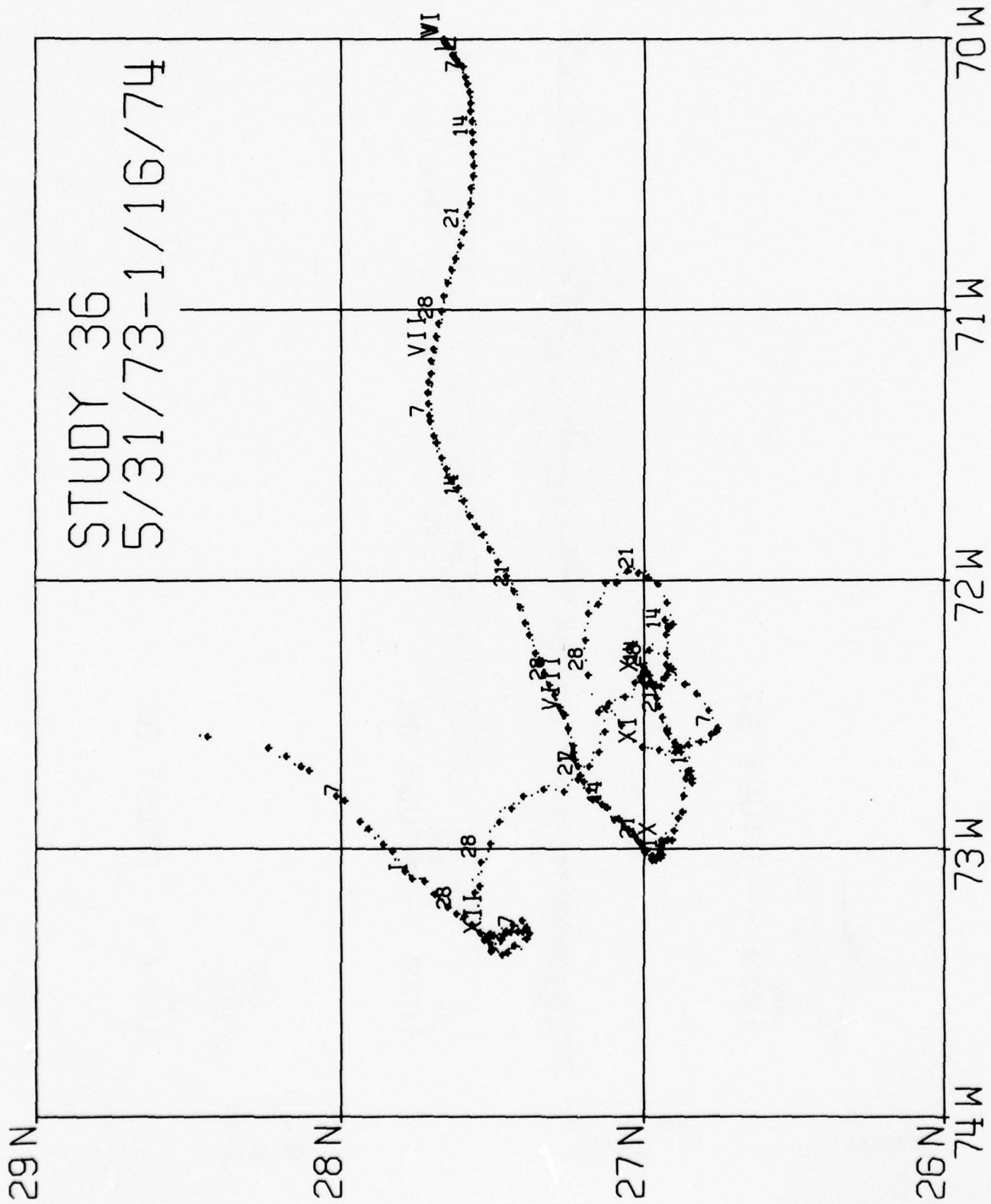
JAN
1974 -- STUDY 35

FEB
MAR

APR
MAY







5 0
CM/SEC



JUN
1973 -- STUDY 36

10 5 0
CM/SEC



JUL
1973 -- STUDY 36

AUG
1973 -- STUDY 36

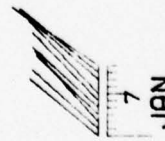
SEP
1973 -- STUDY 36

OCT
1973 -- STUDY 36

NOV
1973 -- STUDY 36

DEC
1973 -- STUDY 36

10 5 0
CM/SEC



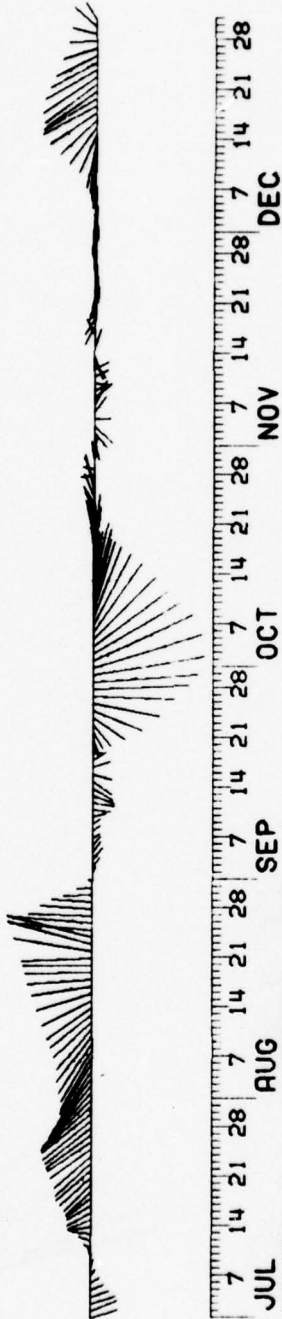
JAN
1974 -- STUDY 36

5 0
CM/SEC



1973 -- STUDY 37

10 5 0
CM/SEC

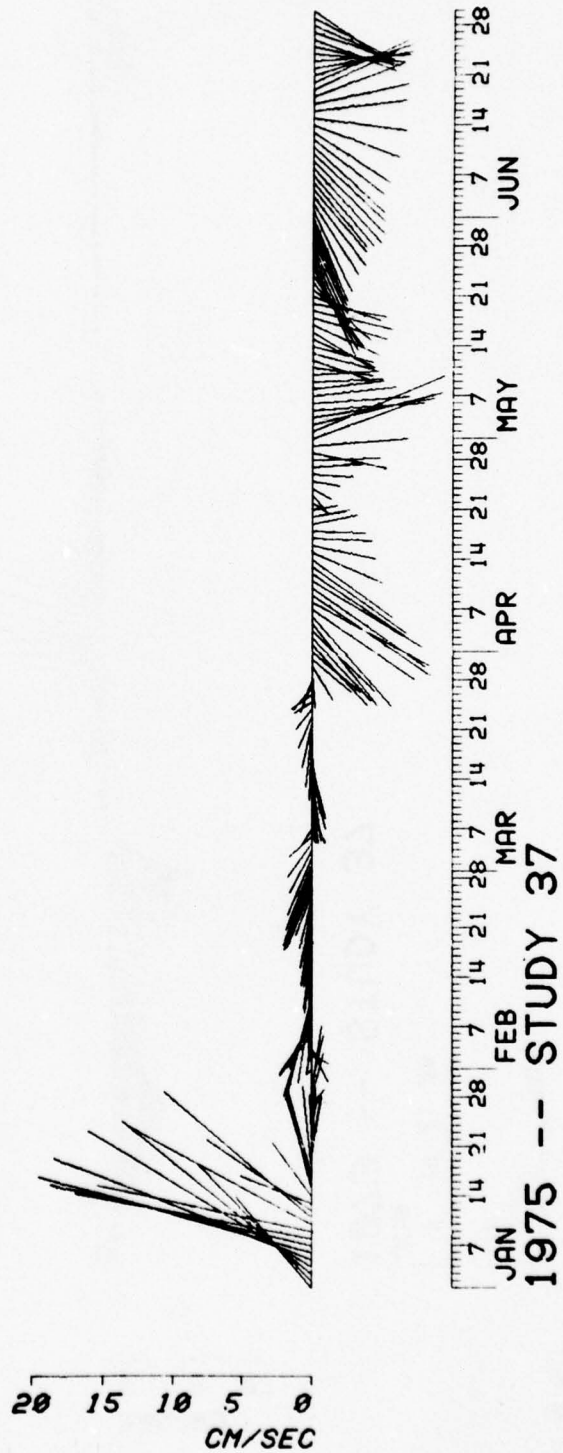
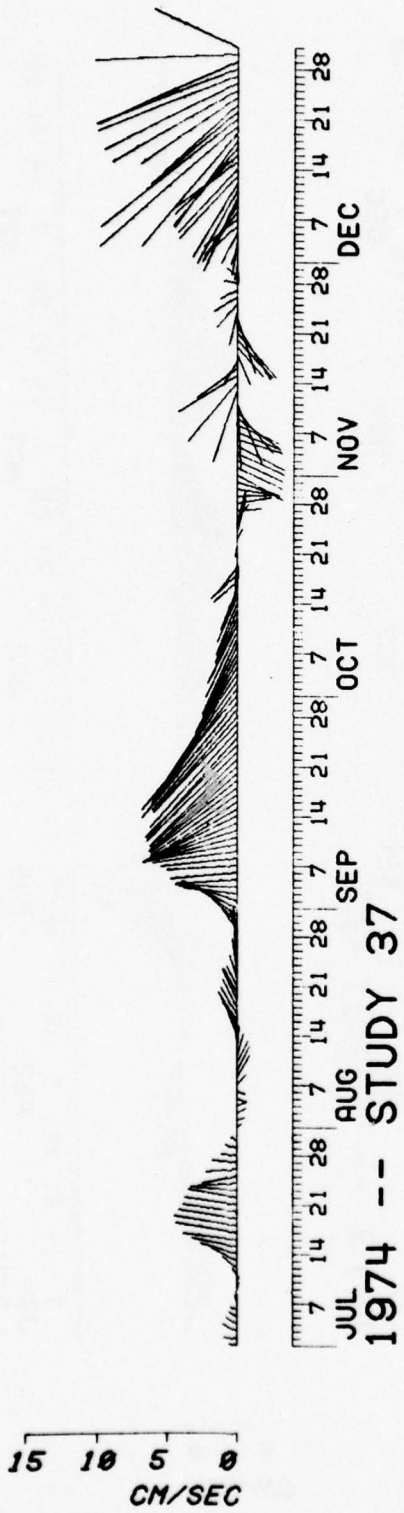


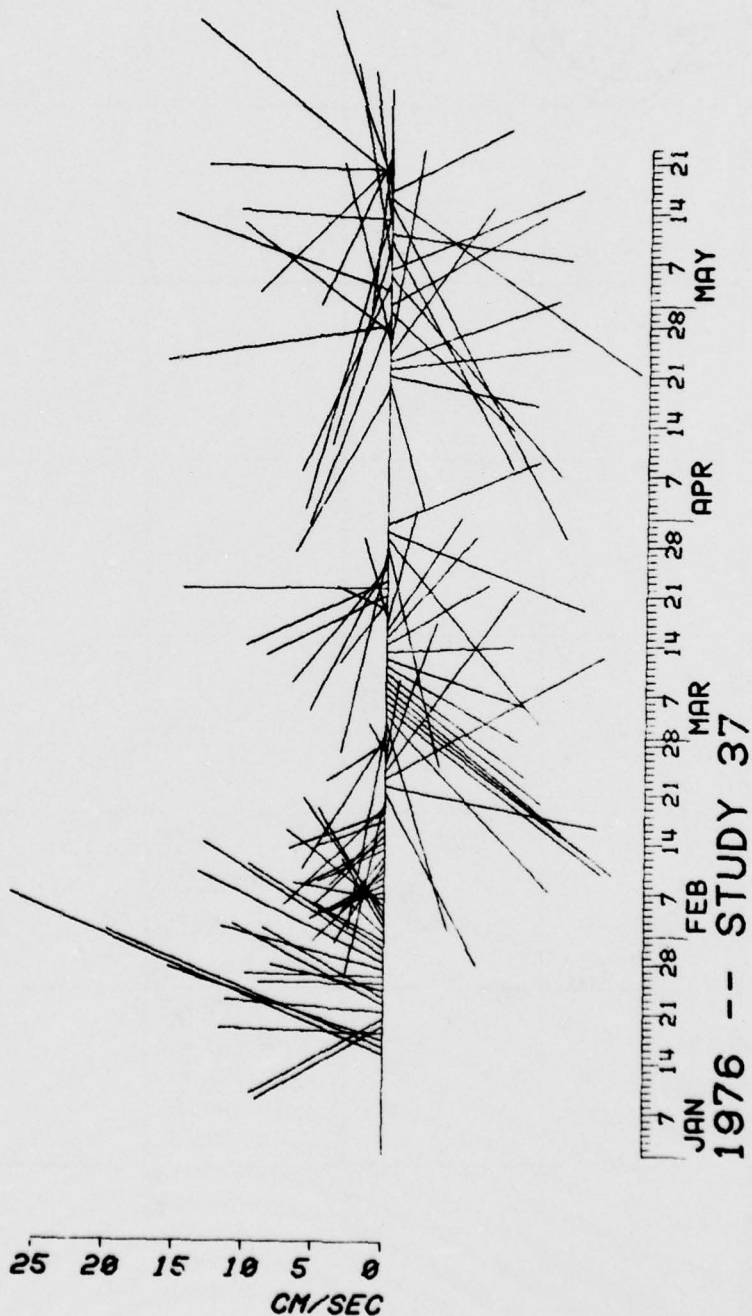
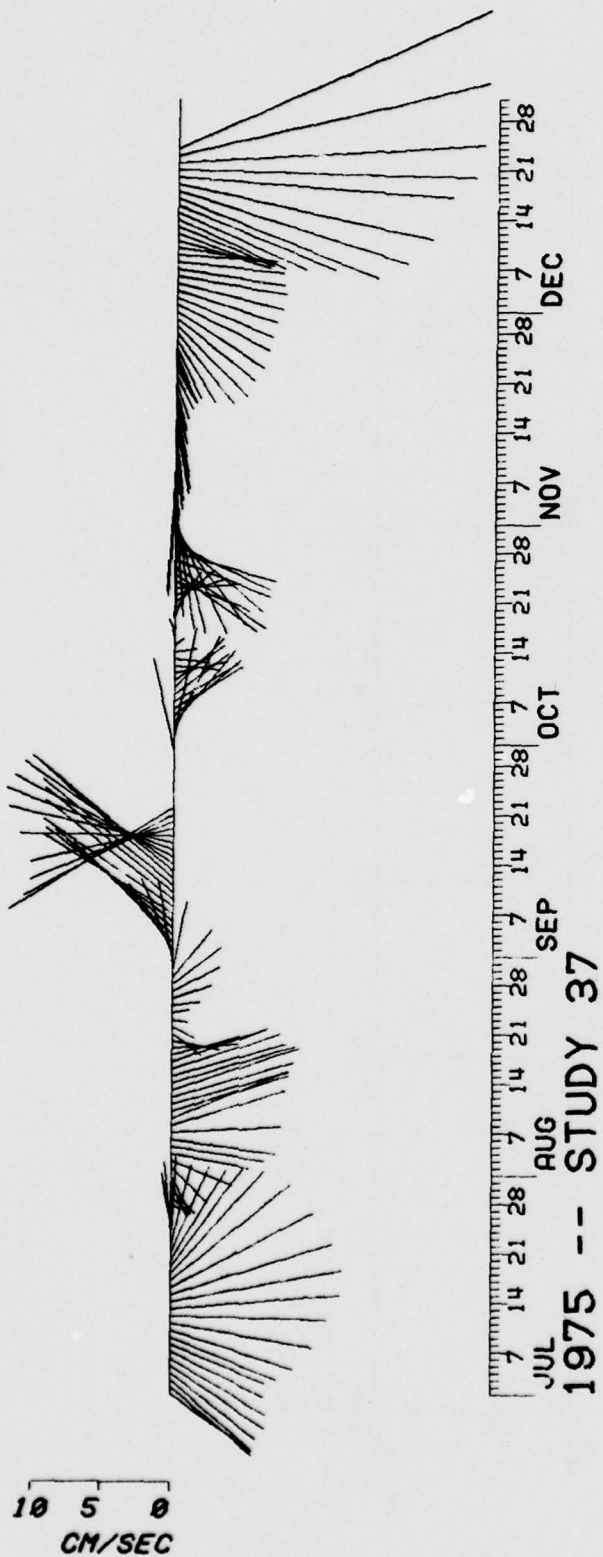
1973 -- STUDY 37

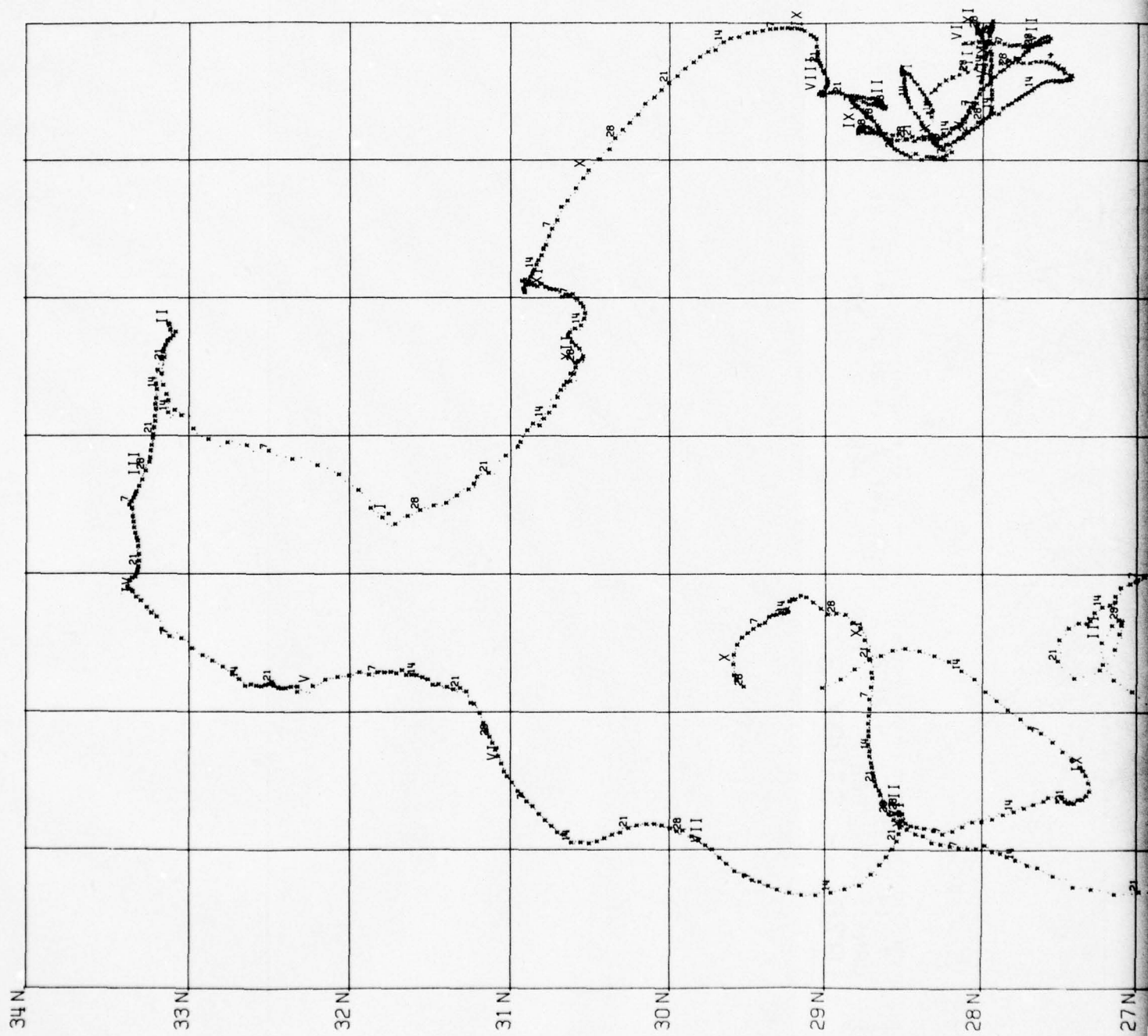
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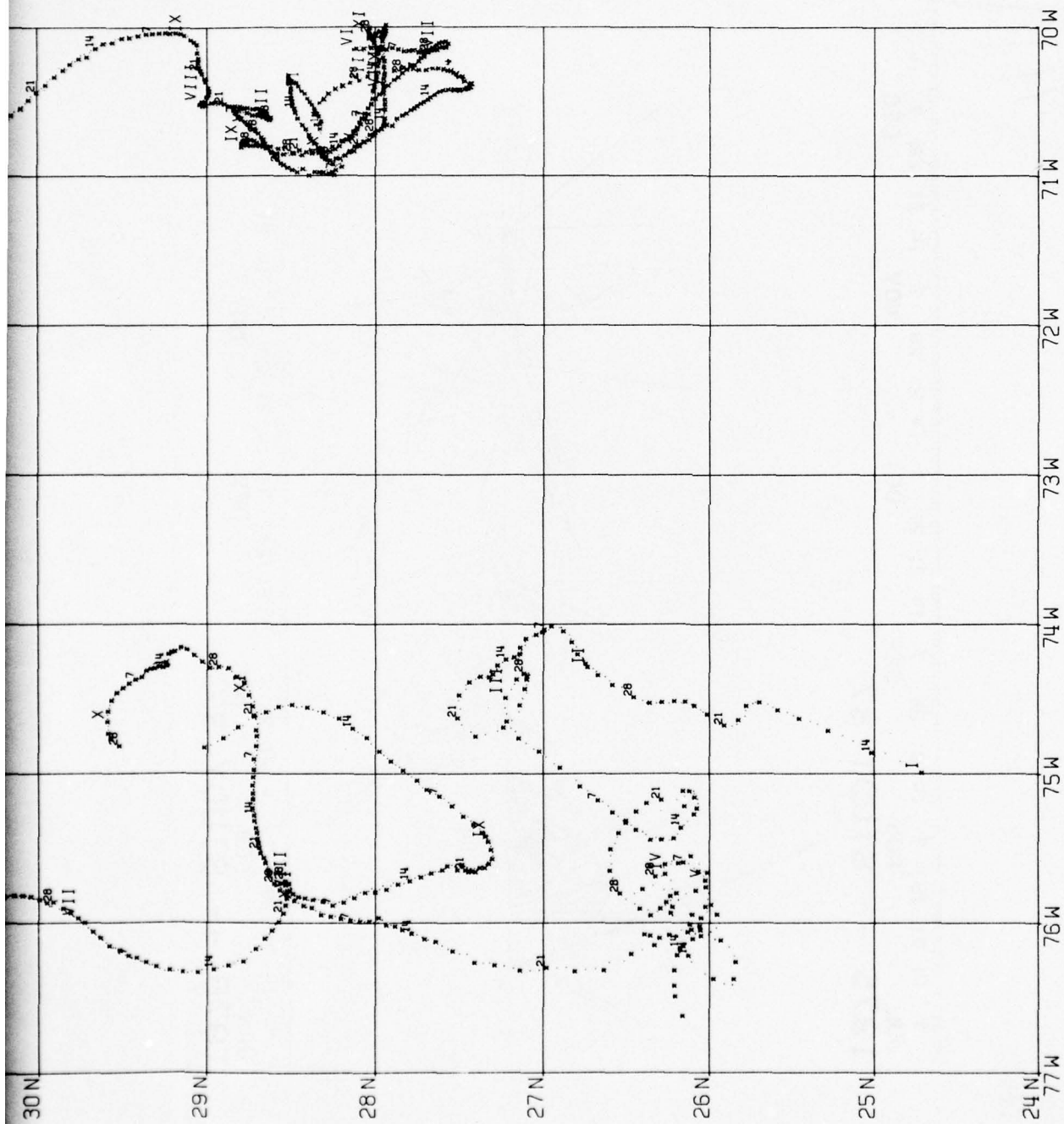


1974 -- STUDY 37

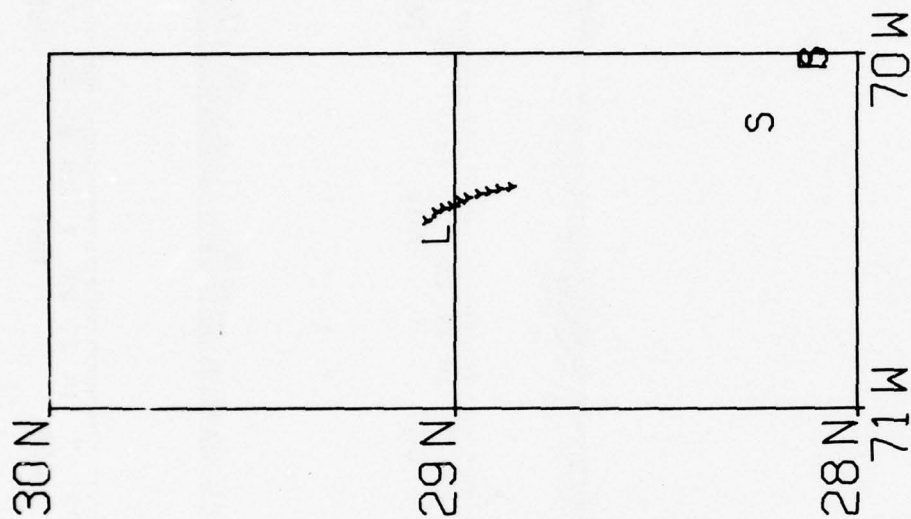








STUDY 37
5/31/73-5/25/75



STUDY 38
6/3/73-7/4/73

5 0
CM/SEC



7 14 21 28

JUN

1973 -- STUDY 38

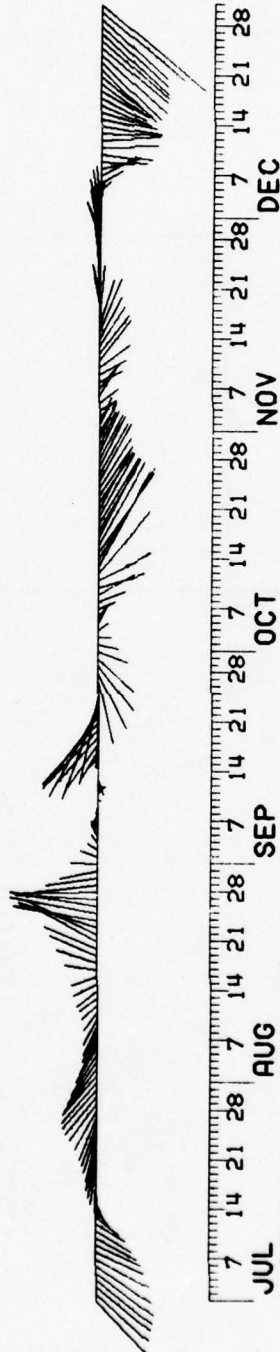
JUL

5 0
CM/SEC



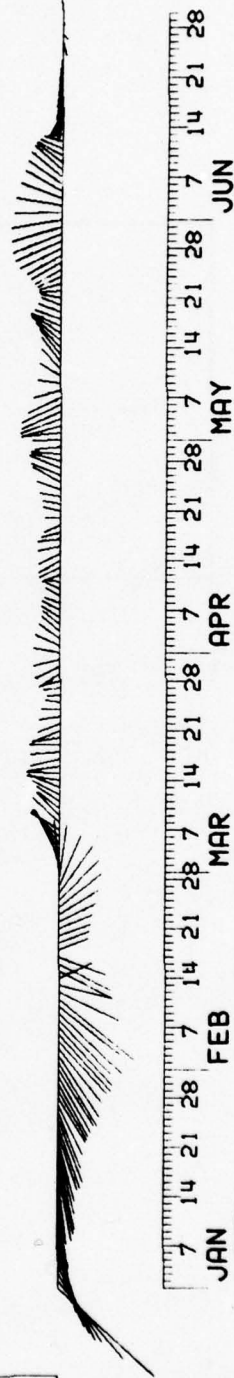
1973 -- STUDY 39

10 5 0
CM/SEC

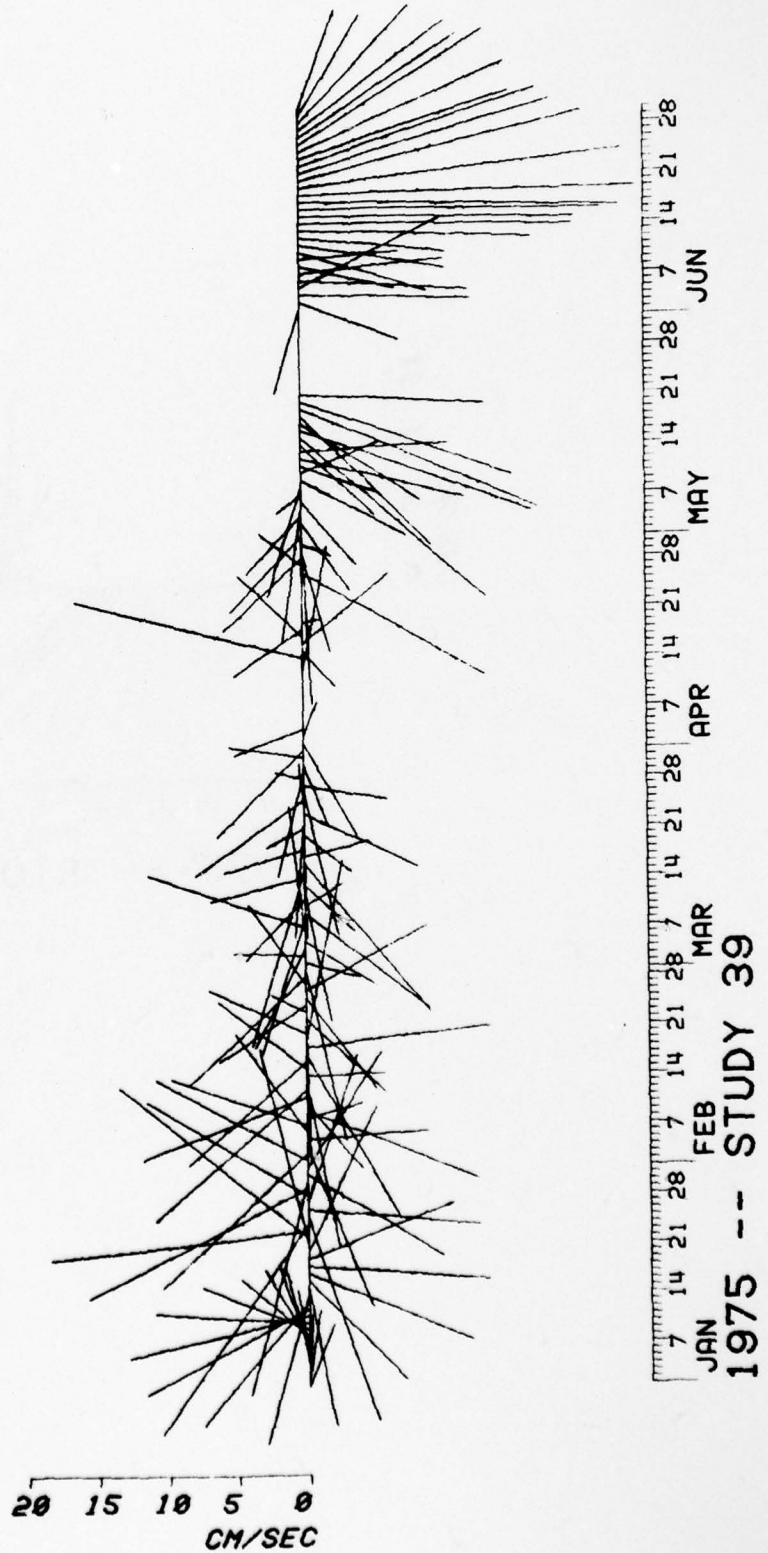
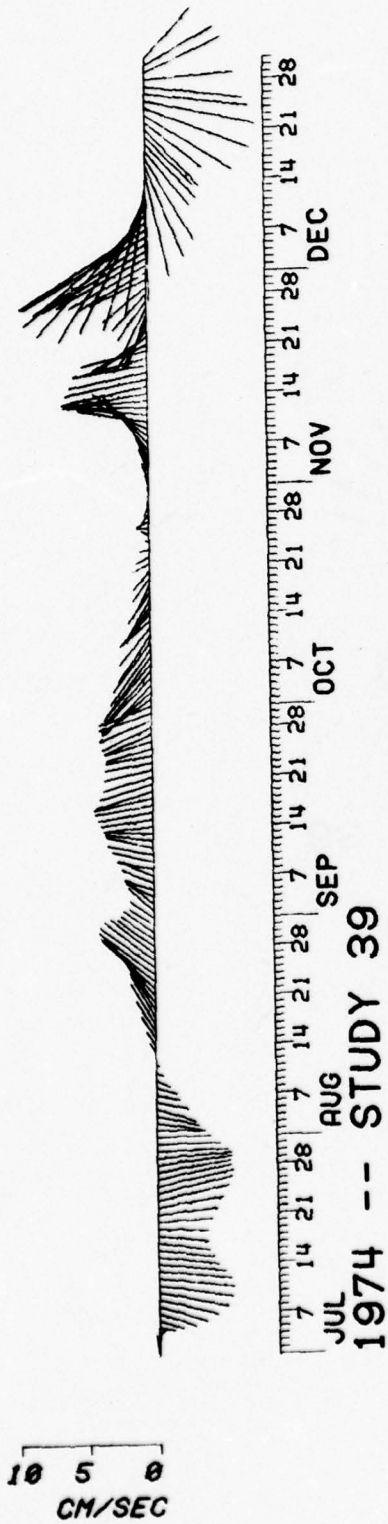


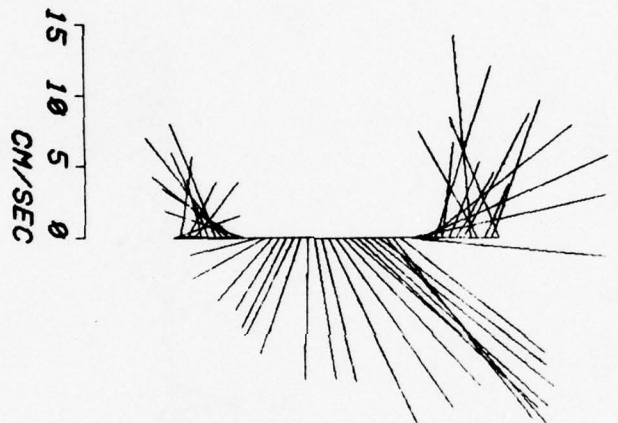
JUL 7 14 21 28
AUG 7 14 21 28
SEP 7 14 21 28
OCT 7 14 21 28
NOV 7 14 21 28
DEC 7 14 21 28
1973 -- STUDY 39

5 0
CM/SEC

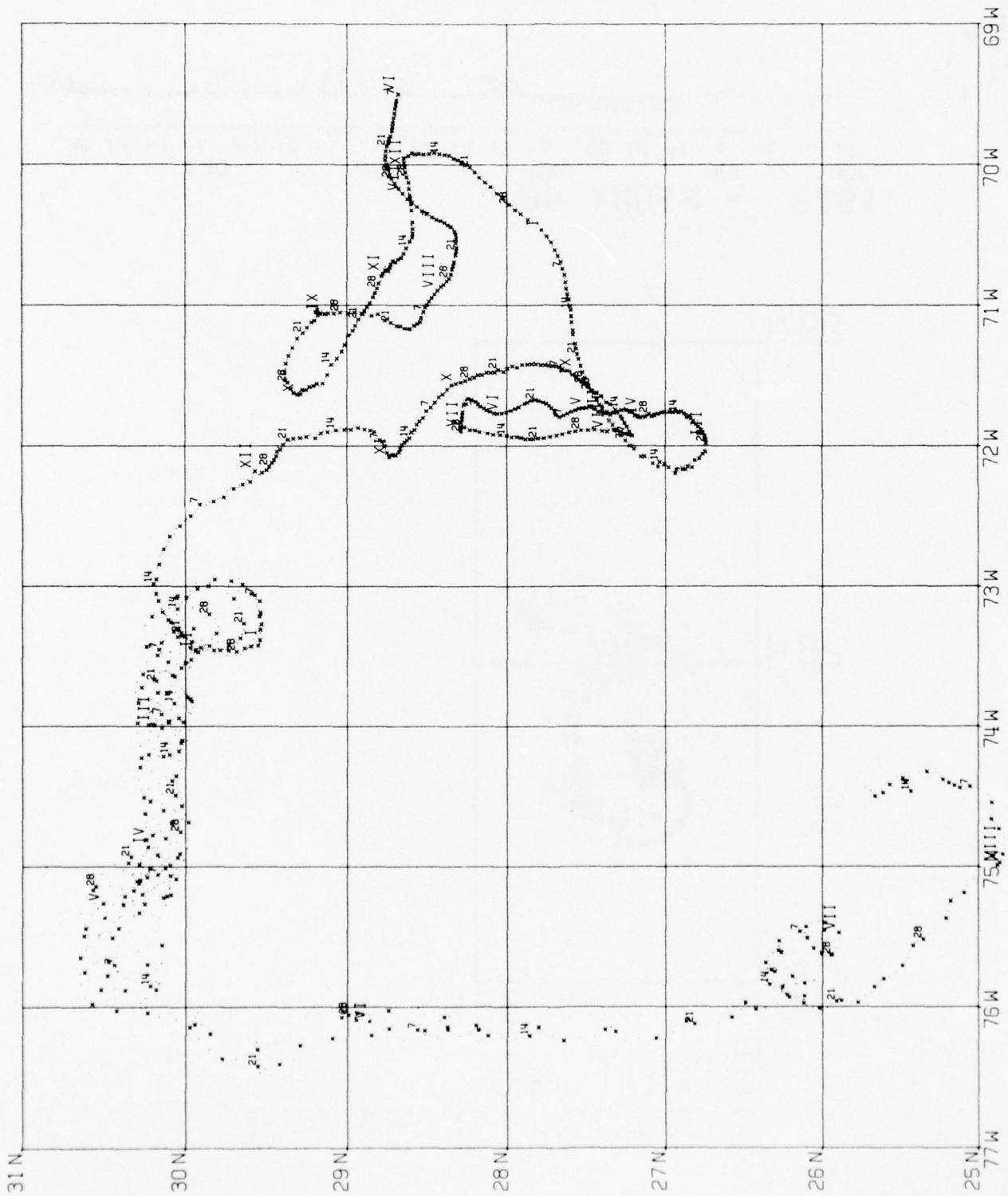


JAN 7 14 21 28
FEB 7 14 21 28
MAR 7 14 21 28
APR 7 14 21 28
MAY 7 14 21 28
JUN 7 14 21 28
1974 -- STUDY 39

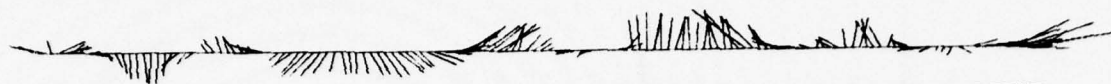




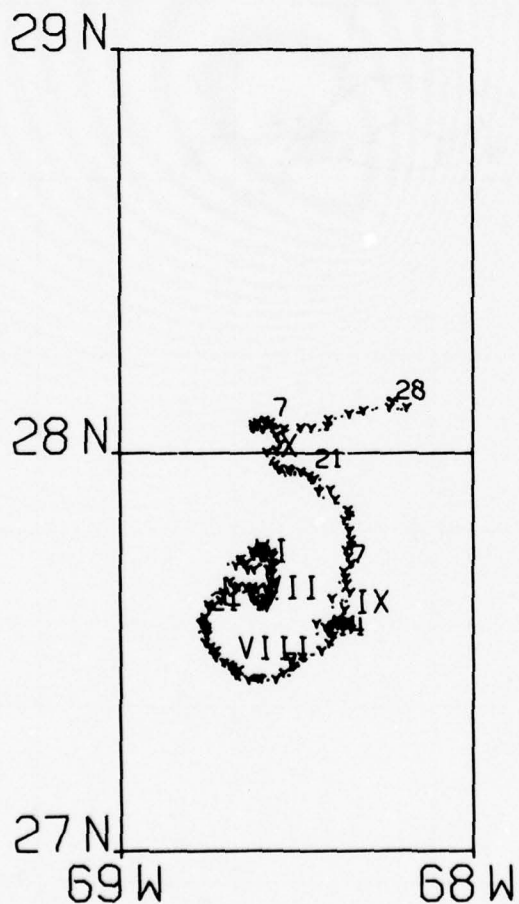
JUL 7 14 21 28 AUG 7 14
1975 -- STUDY 39



STUDY 39
6/5/73-8/18/75

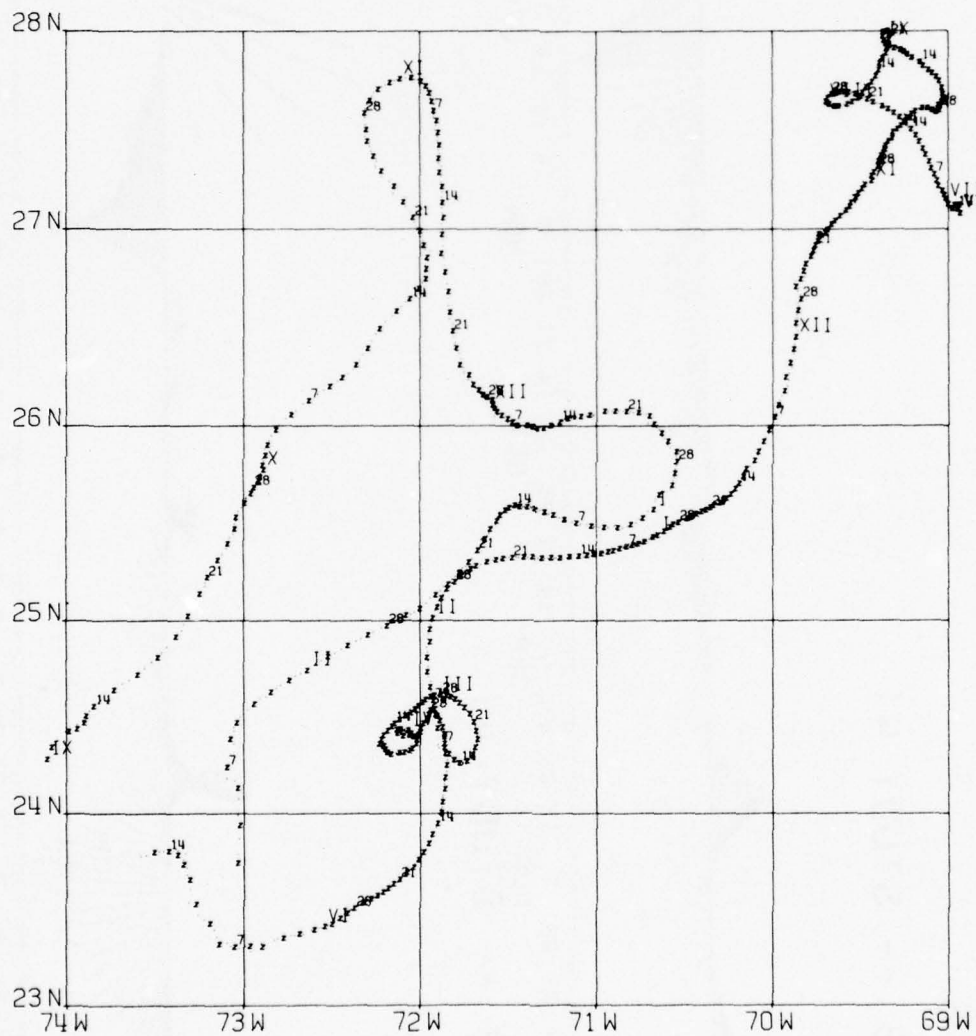
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CM/SEC14 21 28 7 14 21 28 7 14 21 28 7 14 21 28 7 14 21 28
JUN JUL AUG SEP OCT

1973 -- STUDY 40



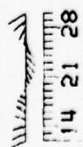
STUDY 40

6/7/73-10/31/73



STUDY 41
6/10/73-2/10/75

5 0
CM/SEC



JUN

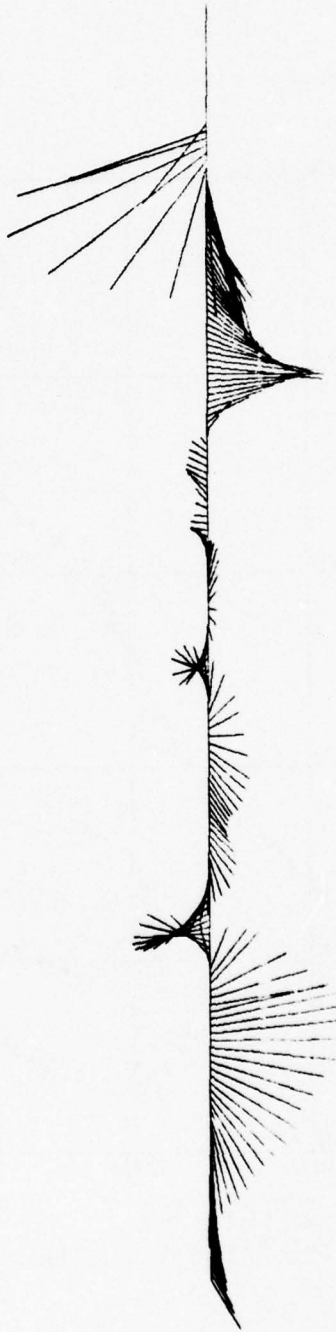
1973 -- STUDY 41

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CM/SEC

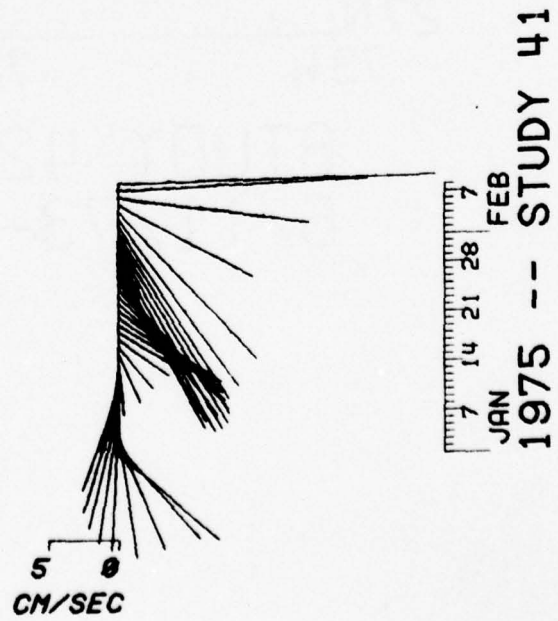
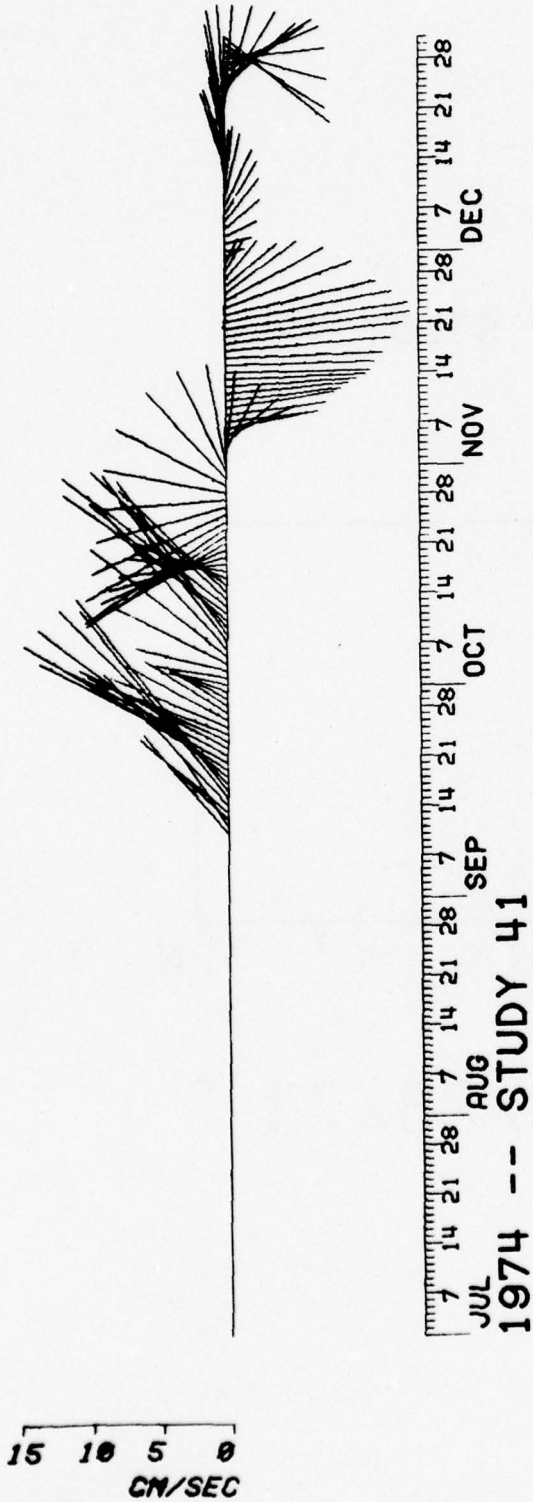


JUL AUG SEP OCT NOV DEC
1973 -- STUDY 41

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CM/SEC



JAN FEB MAR APR MAY JUN
1974 -- STUDY 41

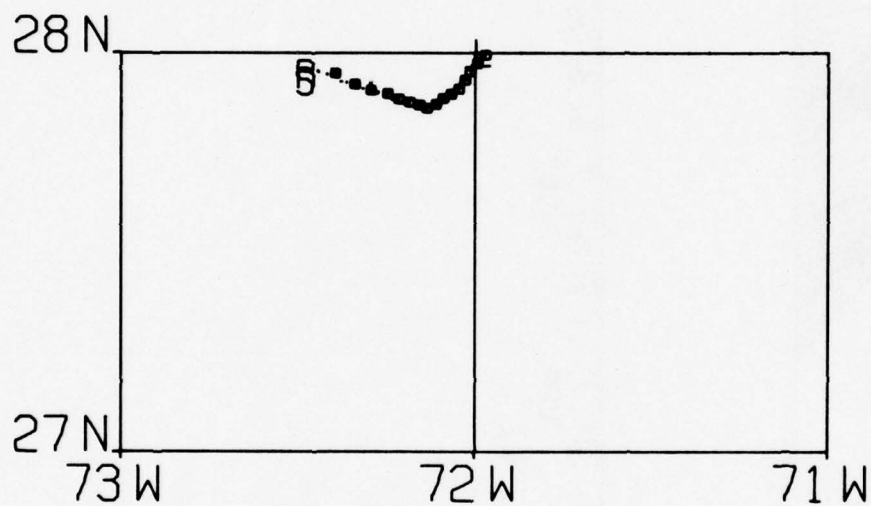


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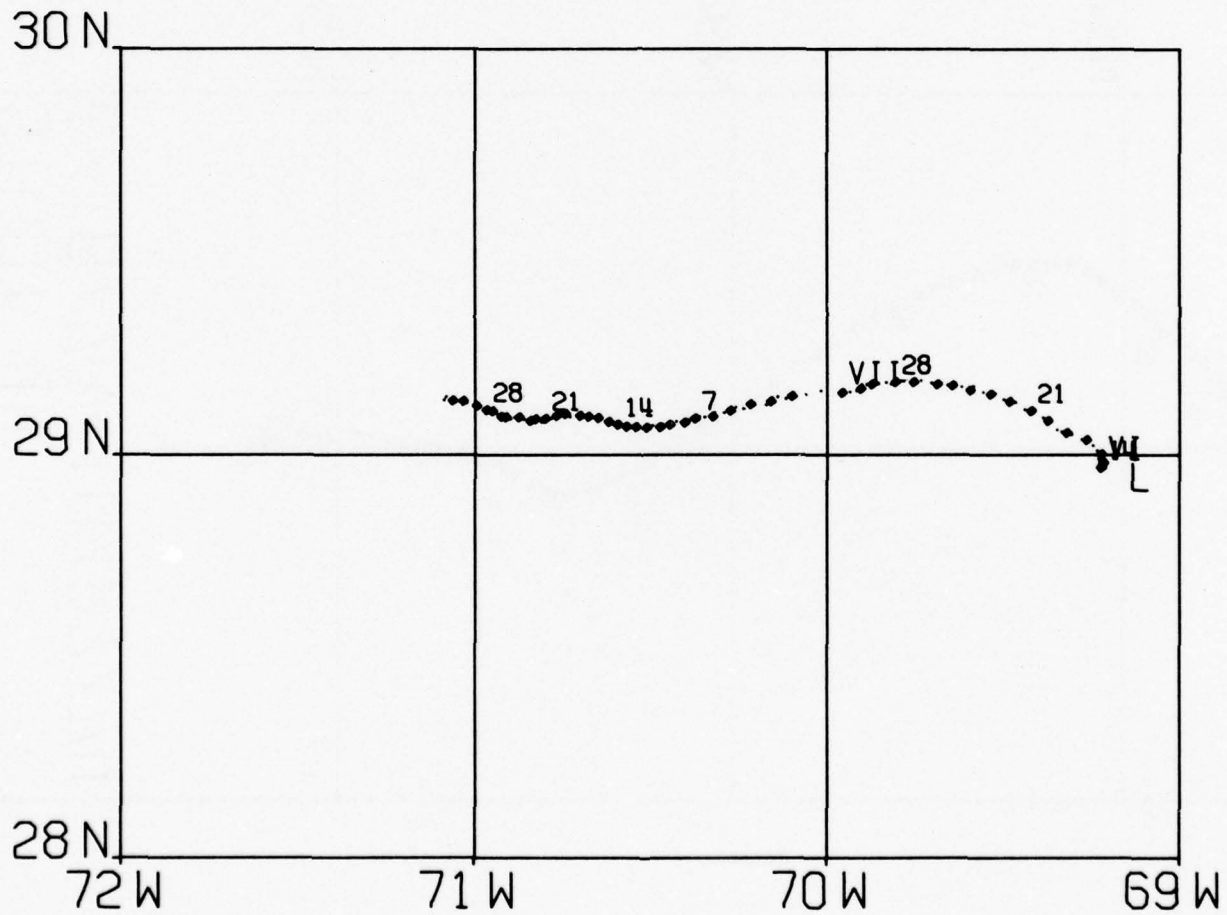


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JUN

1973 -- STUDY 42



STUDY 42
6/11/73-6/28/73



STUDY 43
6/14/73-7/31/73

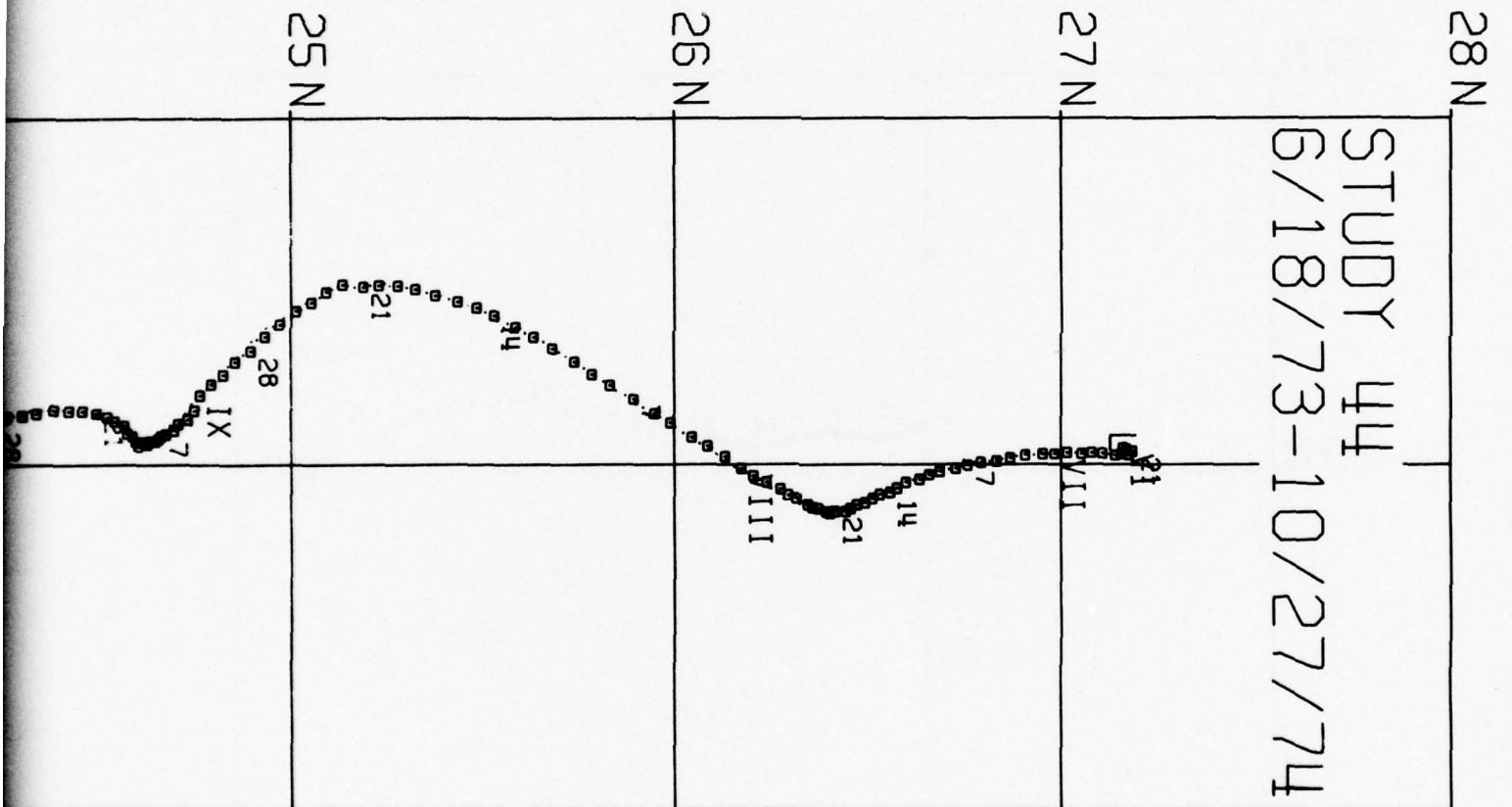
21 N 71 W 70 W 69 W

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CM/SEC

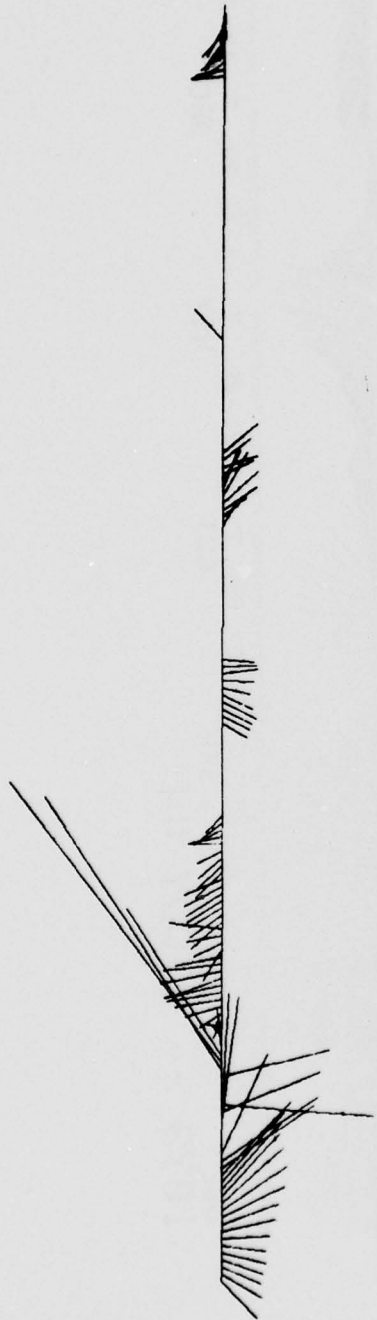


1973 -- STUDY 44

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CM/SEC



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CM/SEC



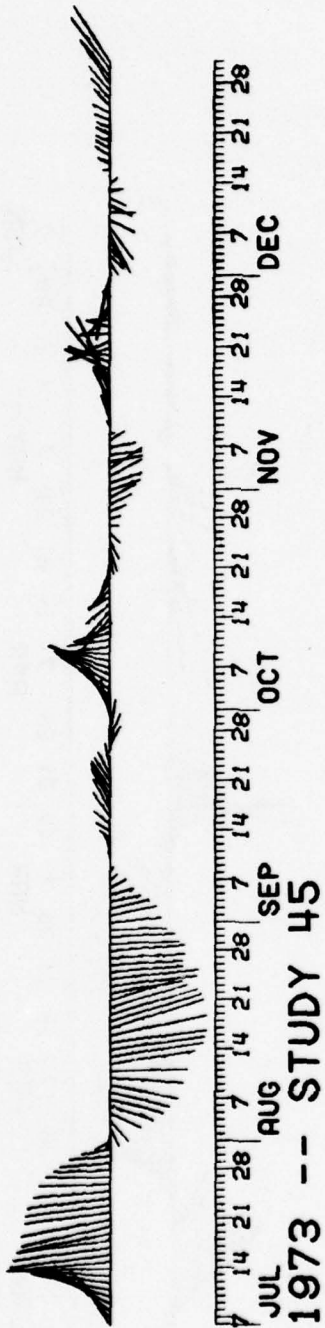
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1974 -- STUDY 44

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CM/SEC

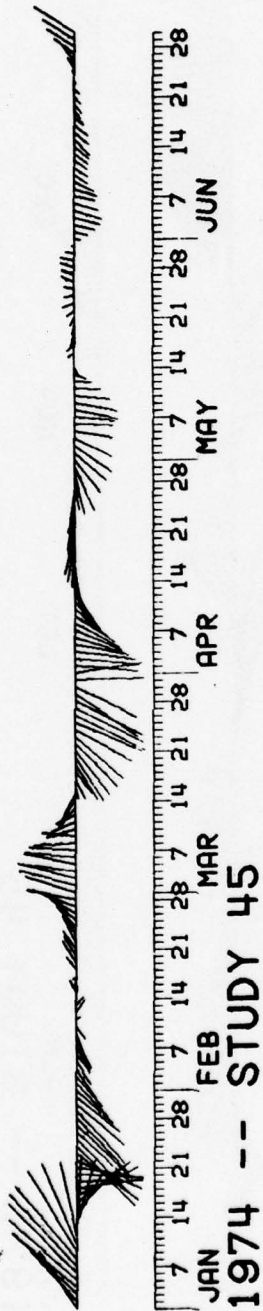


JUL AUG SEP OCT
1974 -- STUDY 44

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CM/SEC



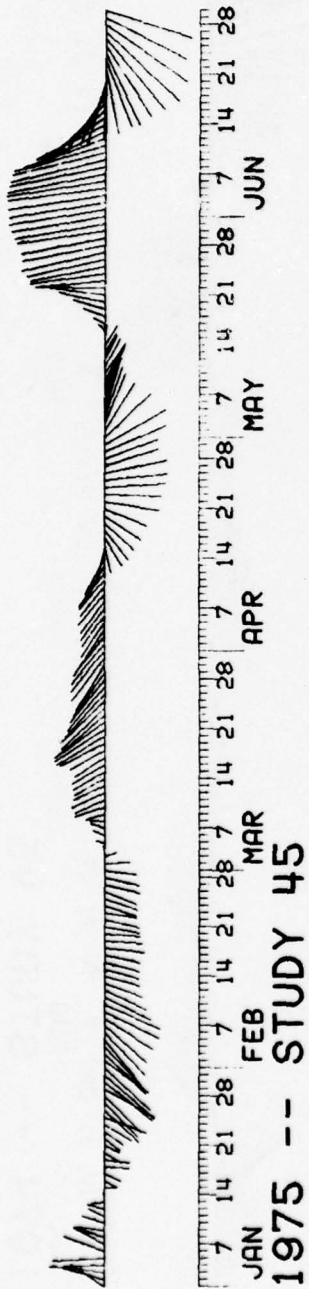
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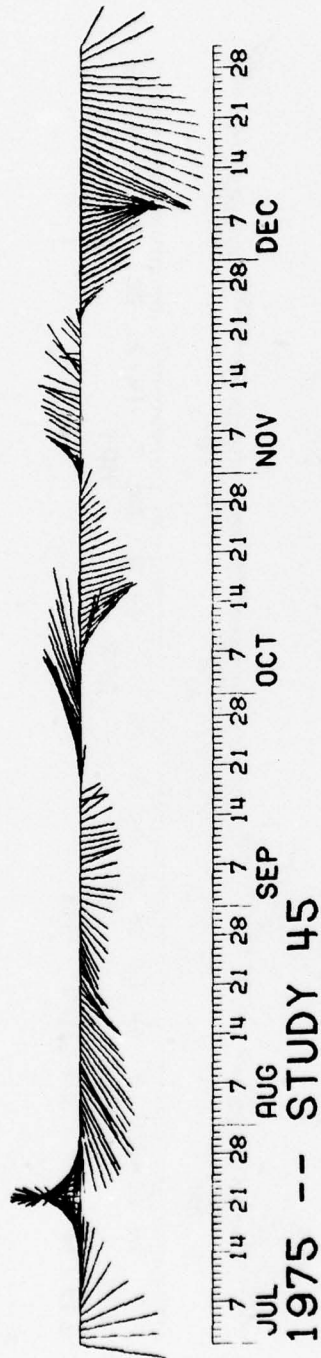
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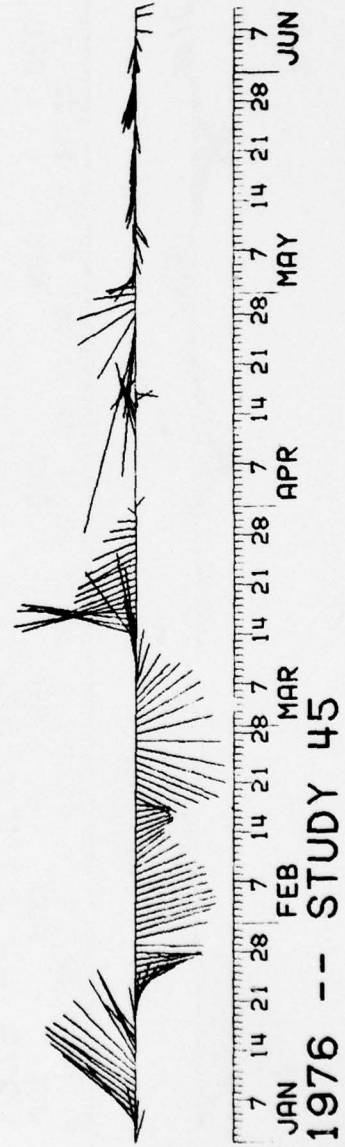
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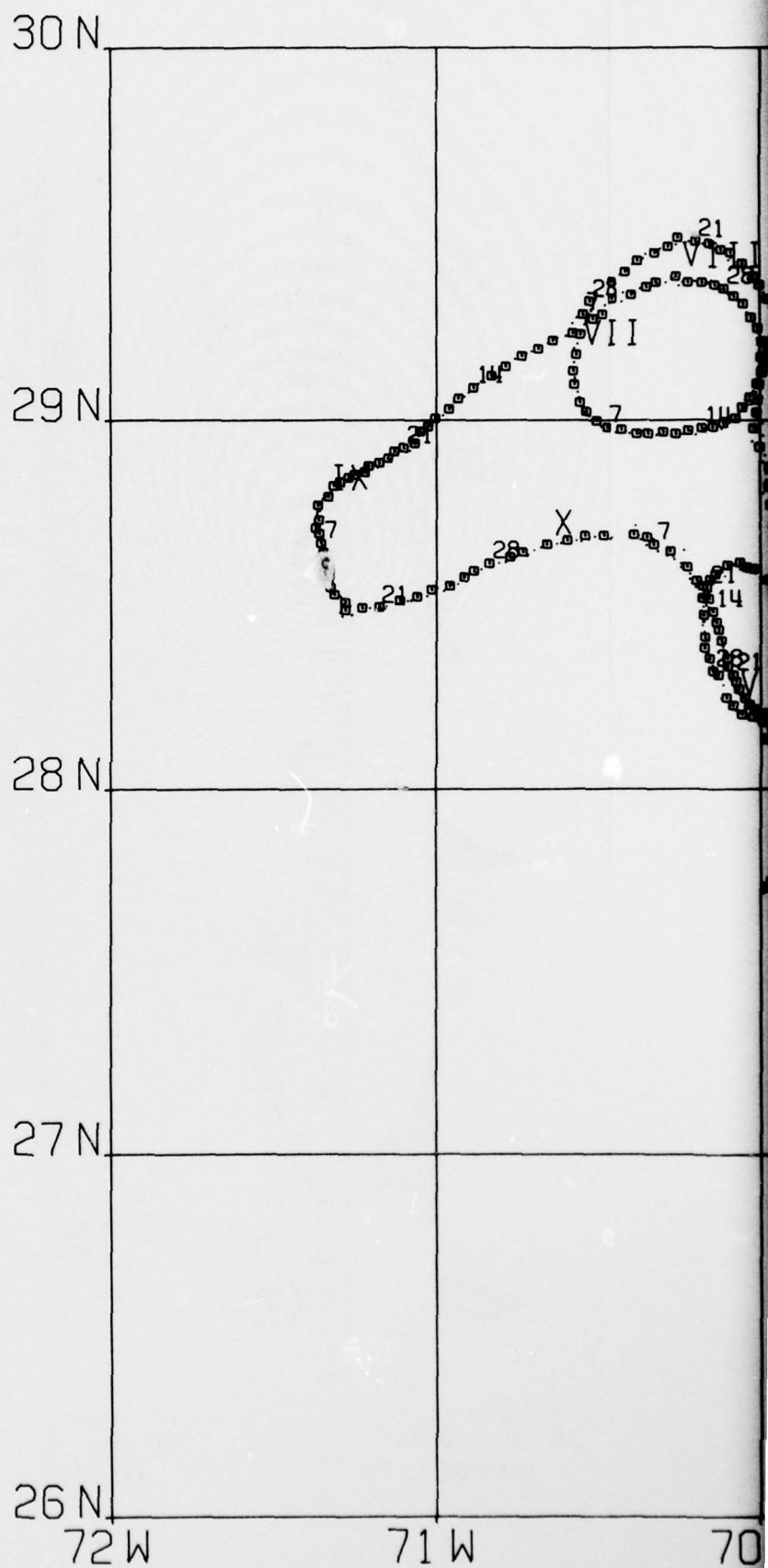


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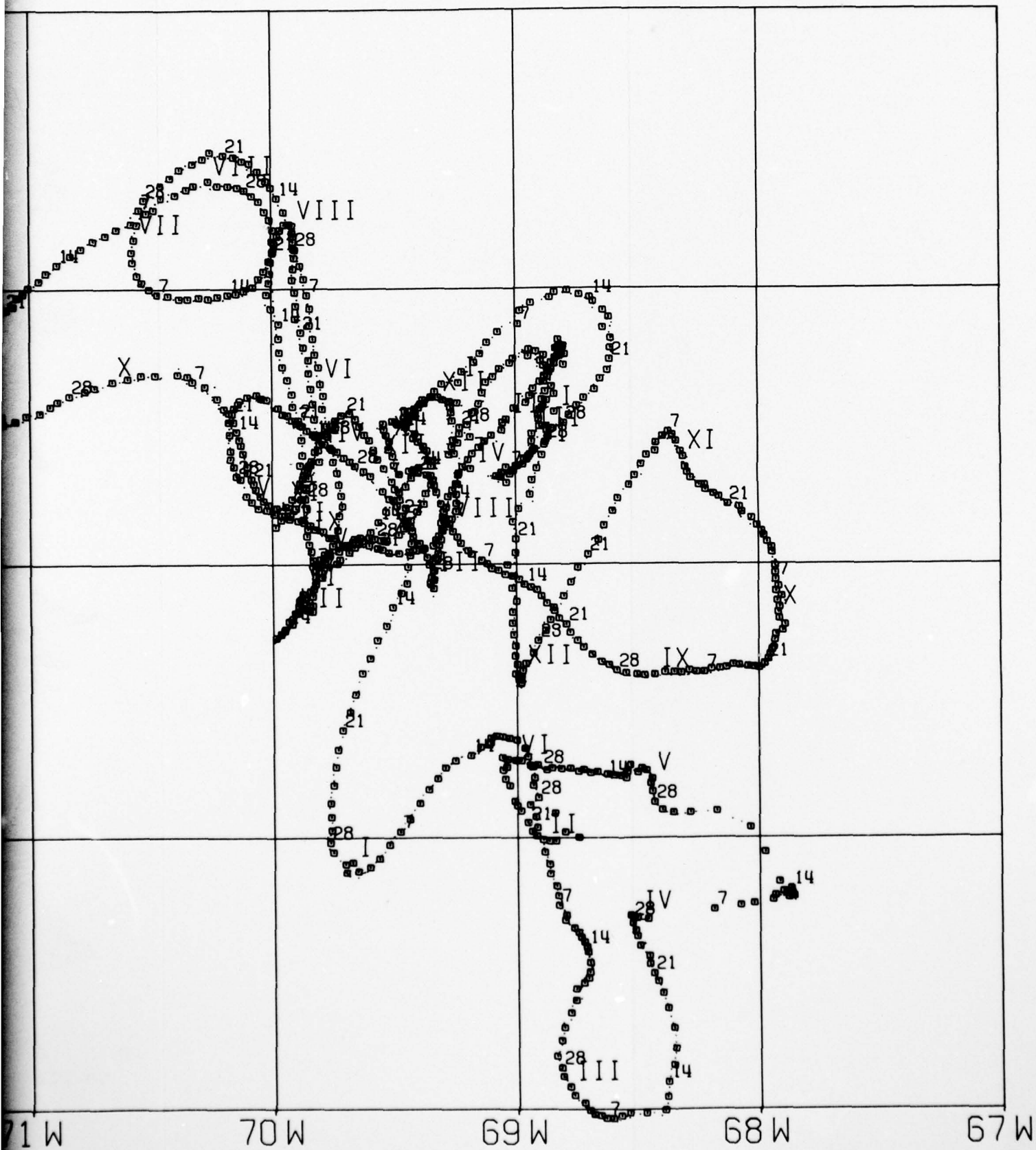


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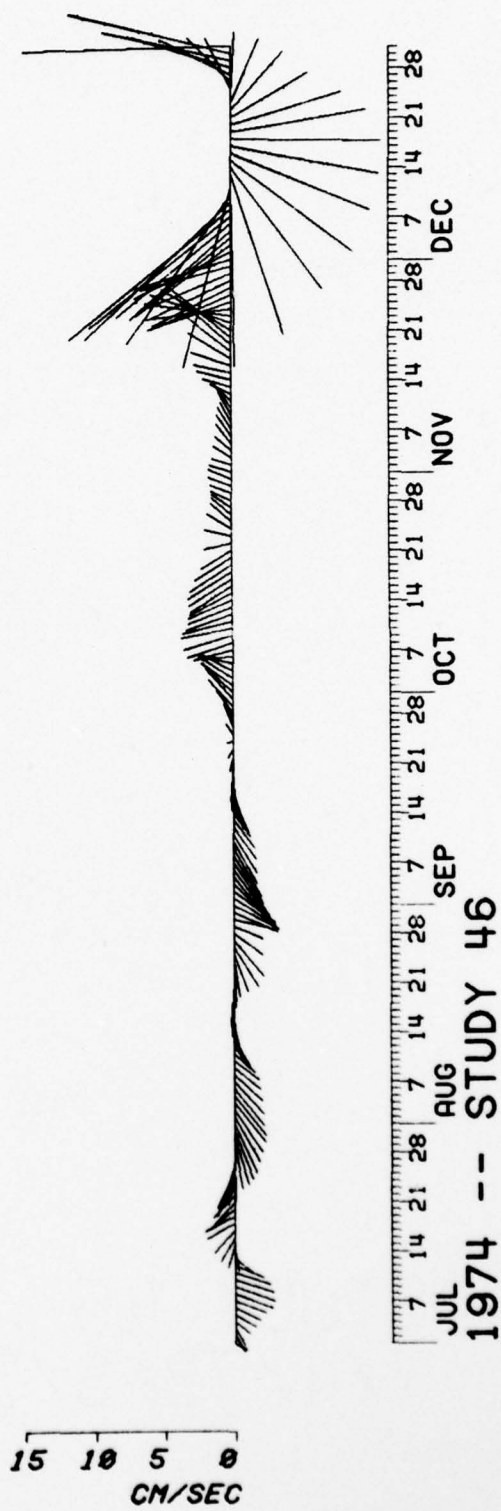
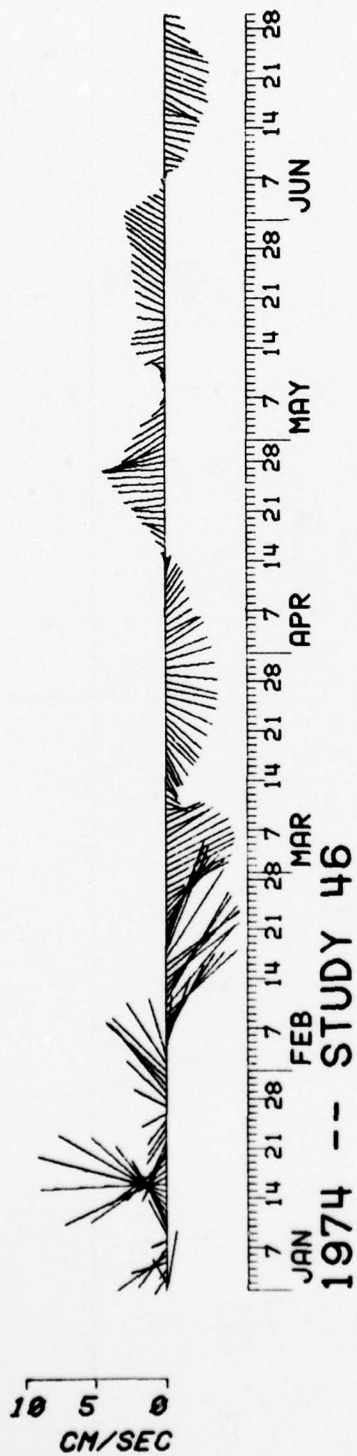
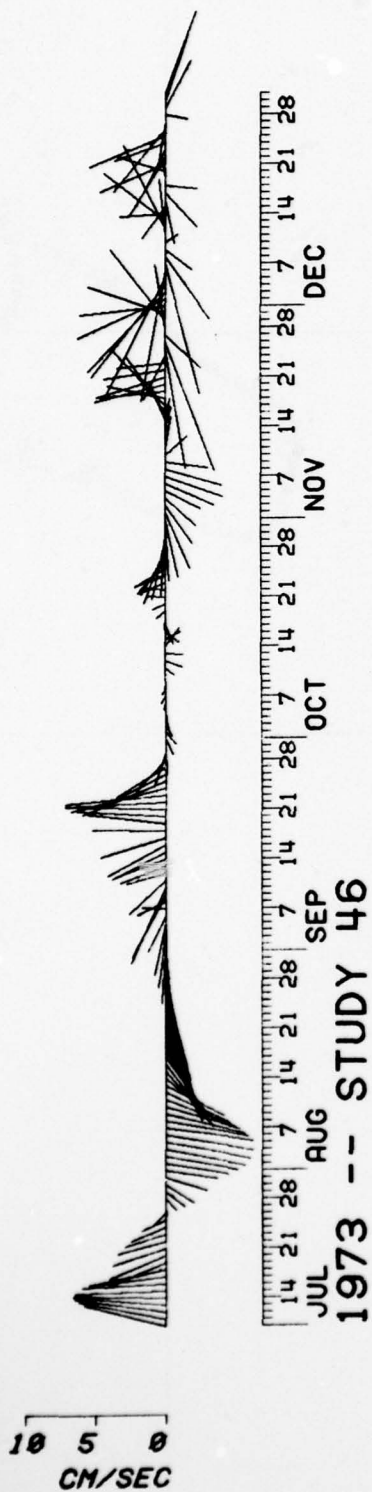




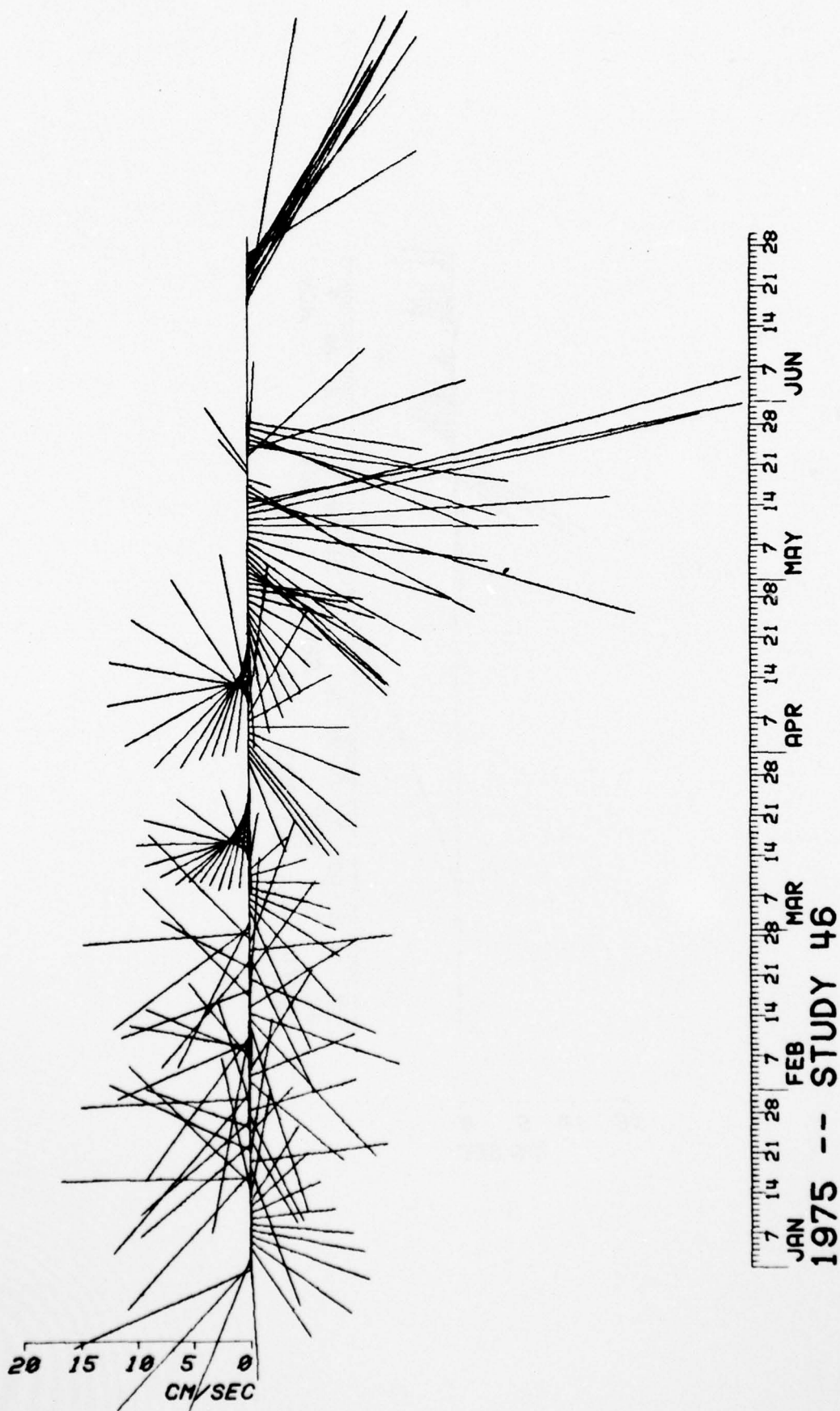
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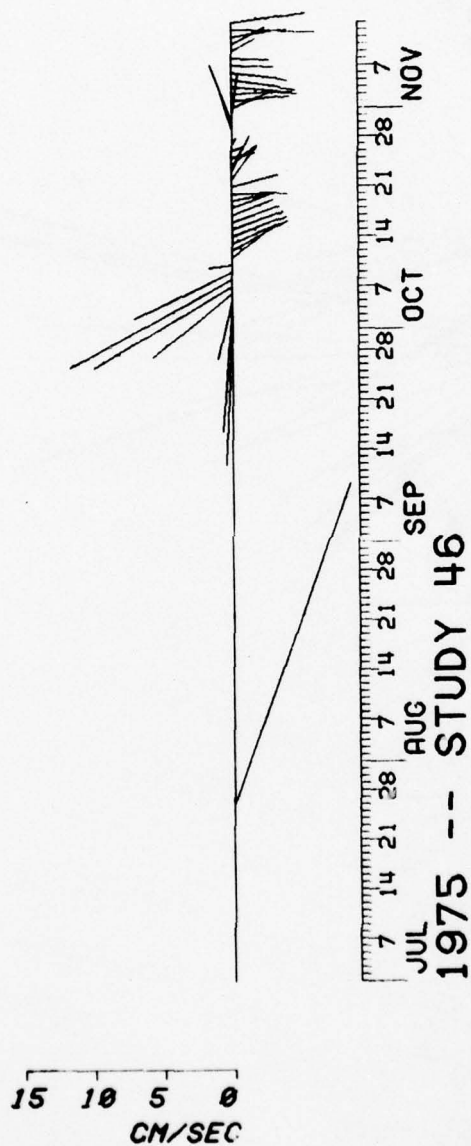


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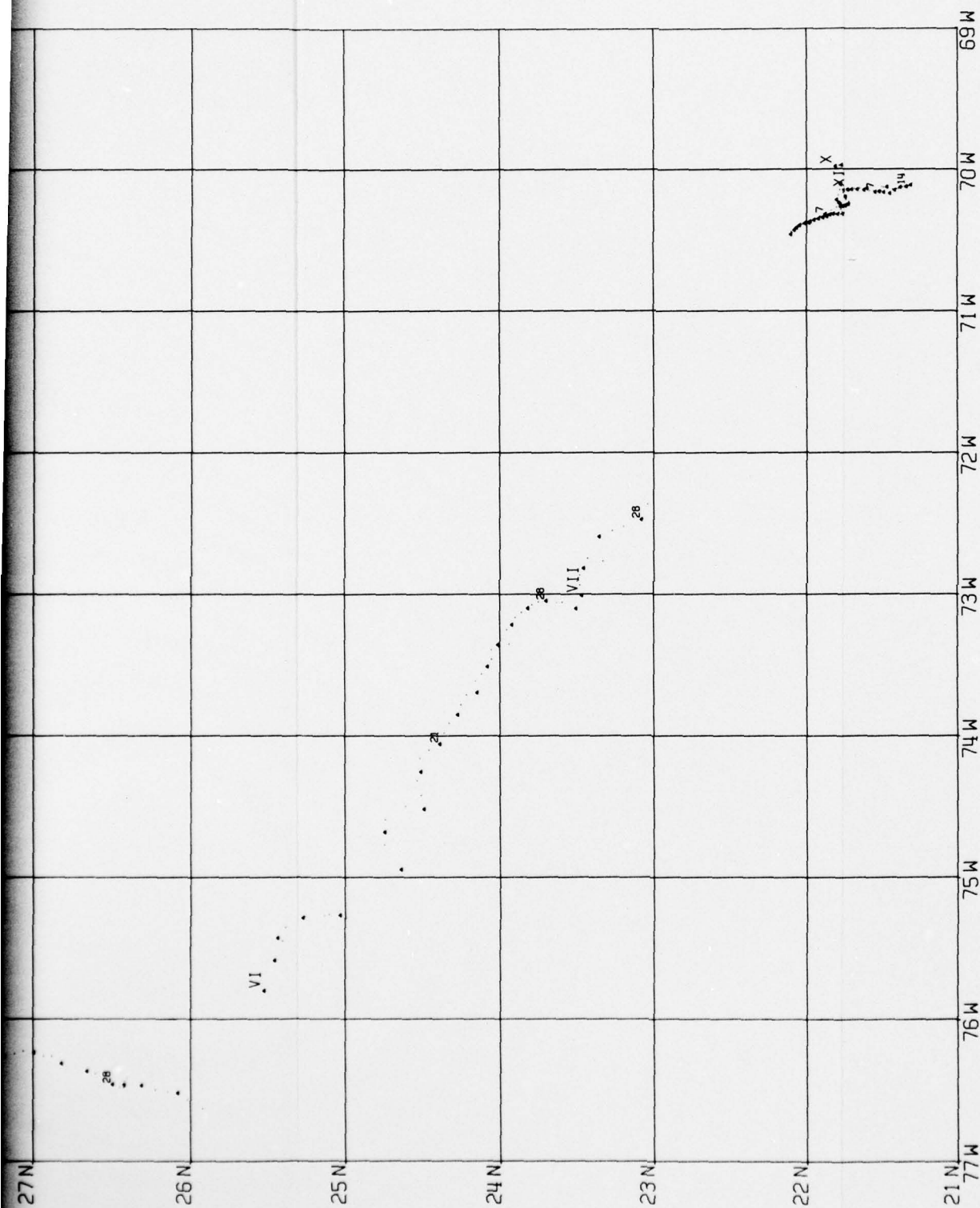


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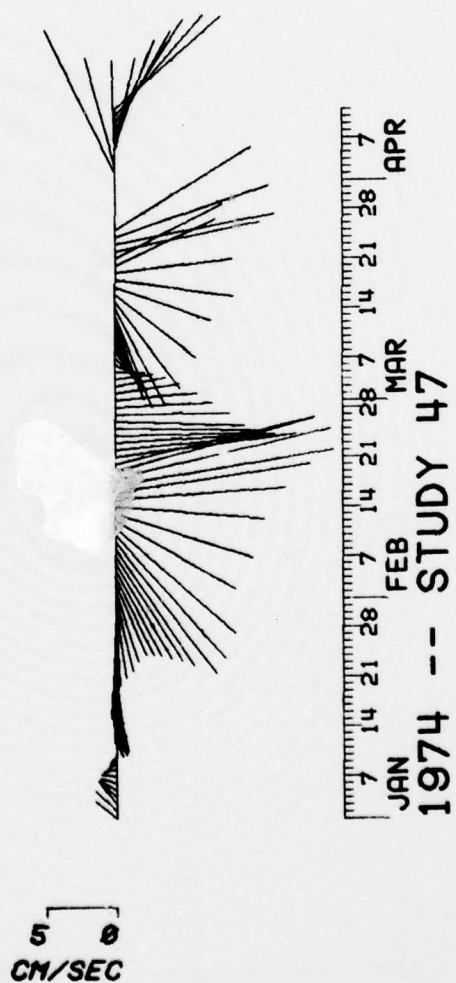
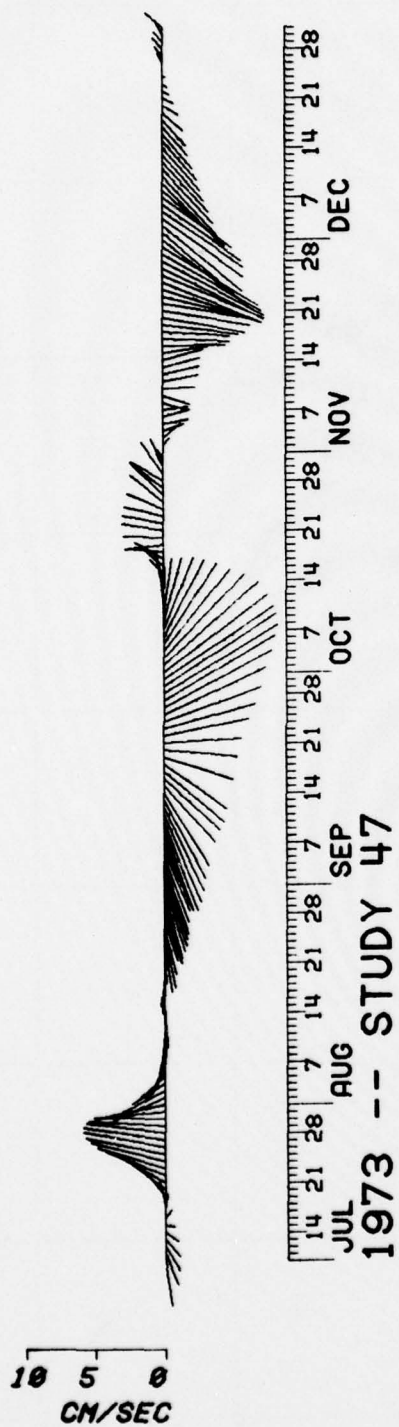


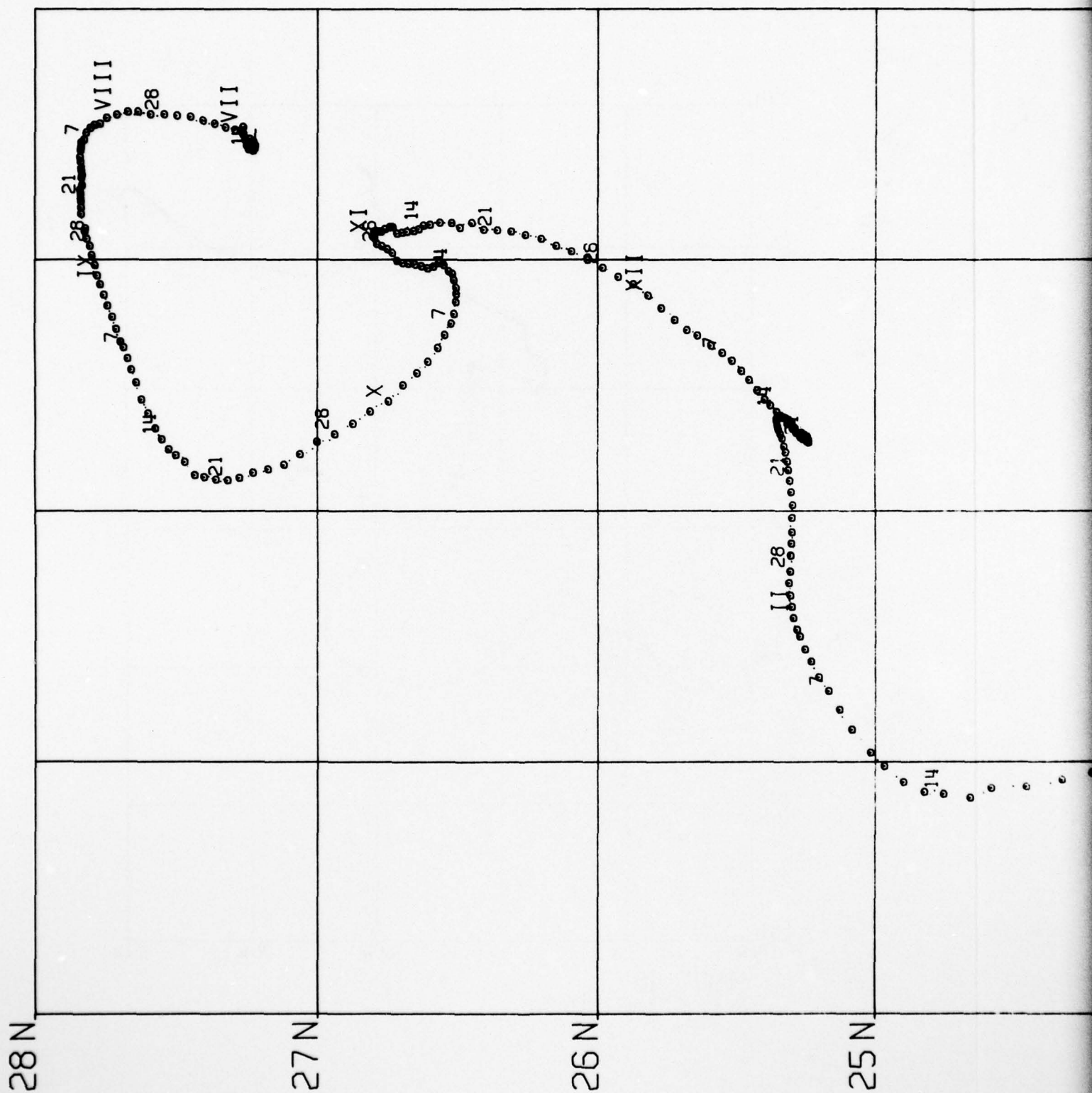


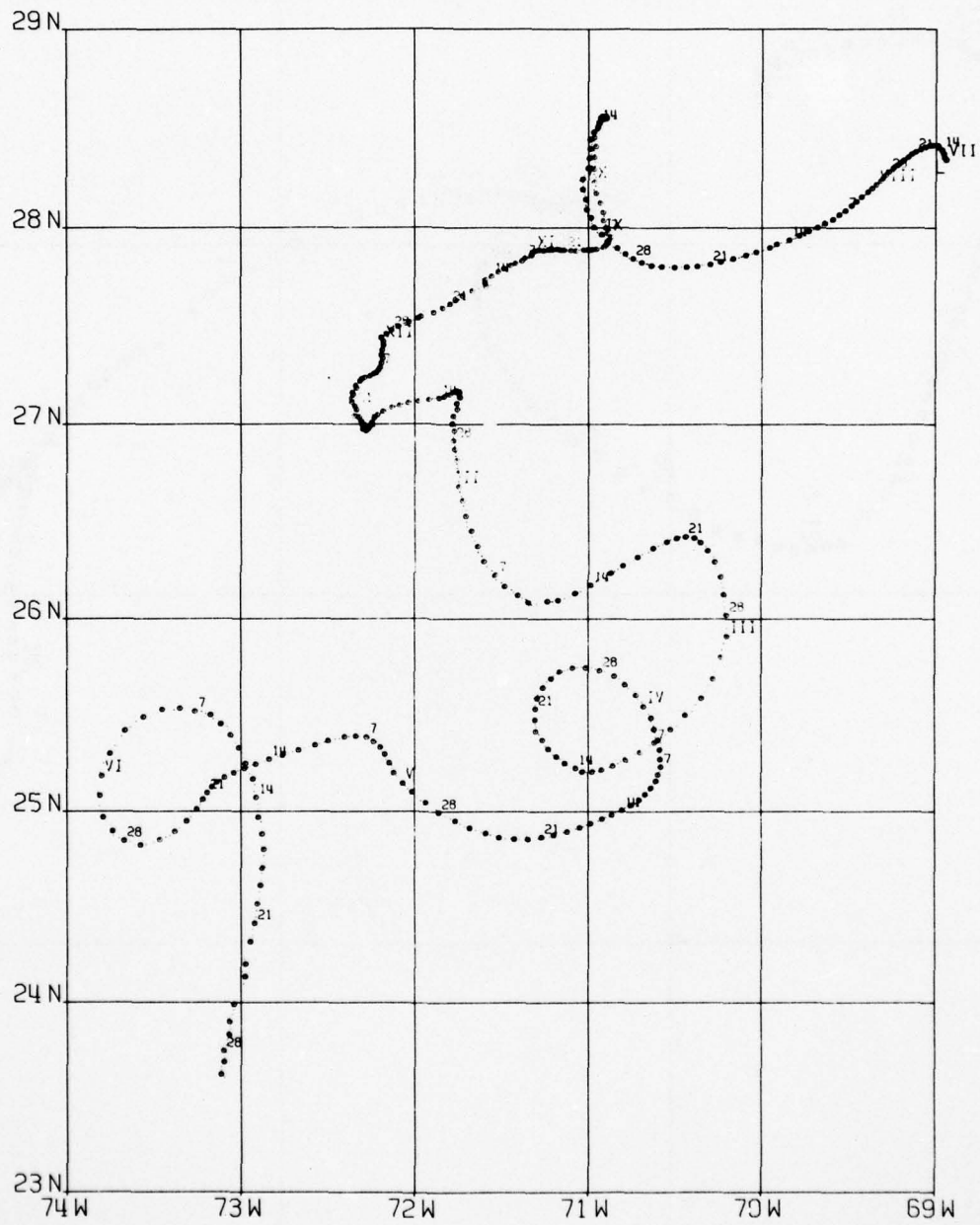


STUDY 46
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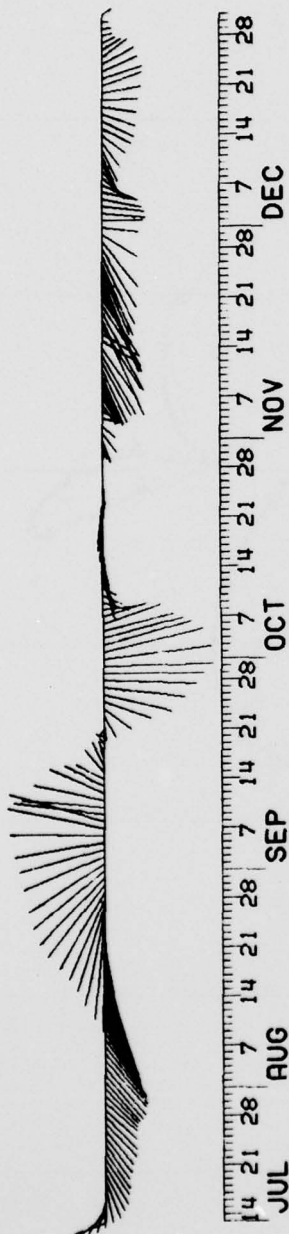




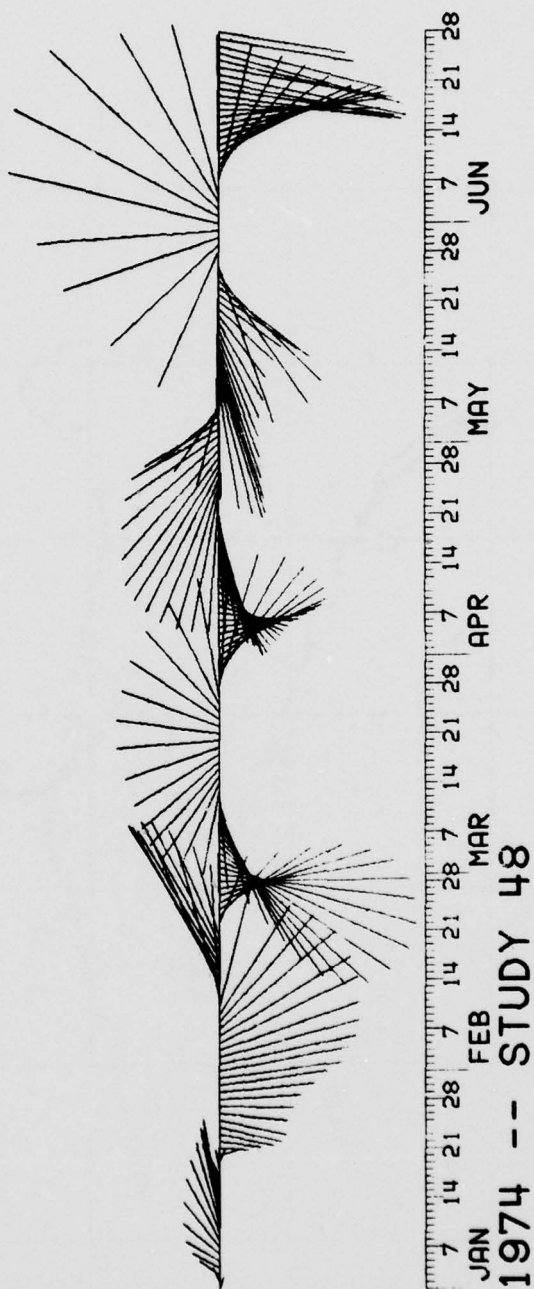


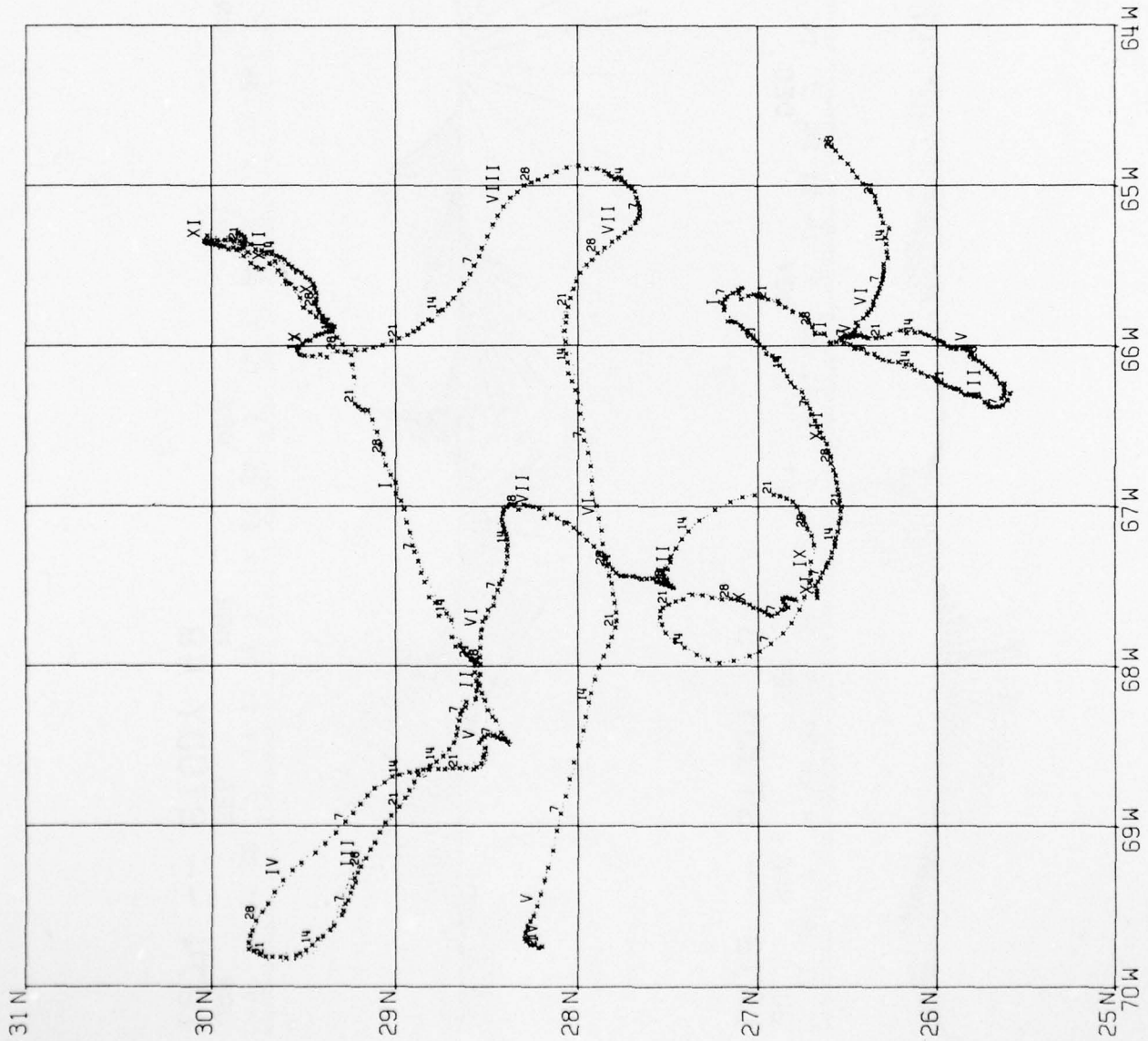
STUDY 48
7/11/73-6/30/74

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CM/SEC



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CM/SEC





STUDY 49
4/19/76-6/30/76

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CM/SEC



21 28 7 14 21 28
MAY JUN

1974 -- STUDY 49

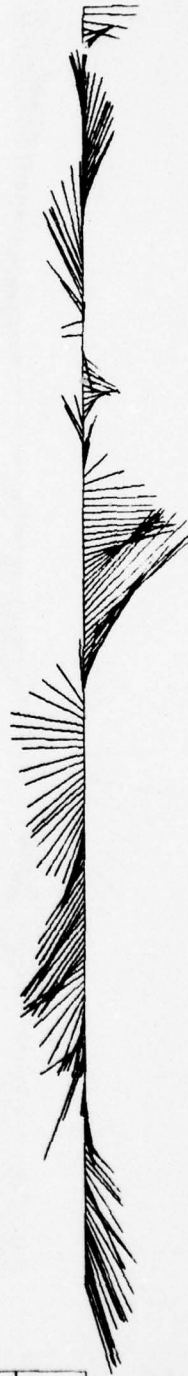
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JUL AUG SEP OCT NOV DEC

1974 -- STUDY 49

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CM/SEC



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JAN FEB MAR APR MAY JUN

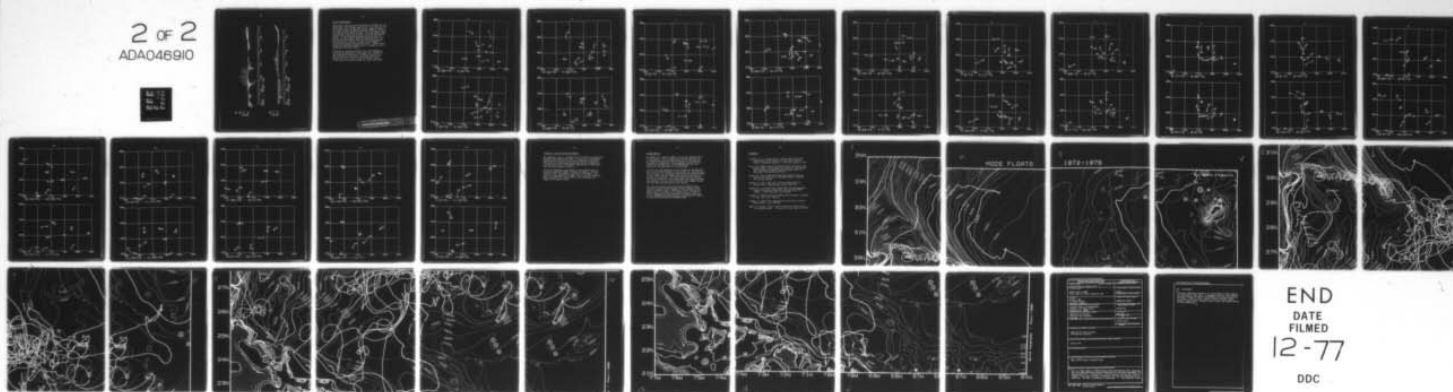
1975 -- STUDY 49

AD-A046 910

RHODE ISLAND UNIV KINGSTON GRADUATE SCHOOL OF OCEANO--ETC F/G 17/1
SOFAR FLOATS IN MODE, FINAL REPORT OF FLOAT TRAJECTORY DATA.(U)
MAY 77 D L DOW, H T ROSSBY, S R SIGNORINI N00014-76-C-0226
URI/GSO-REF-77-3 NL

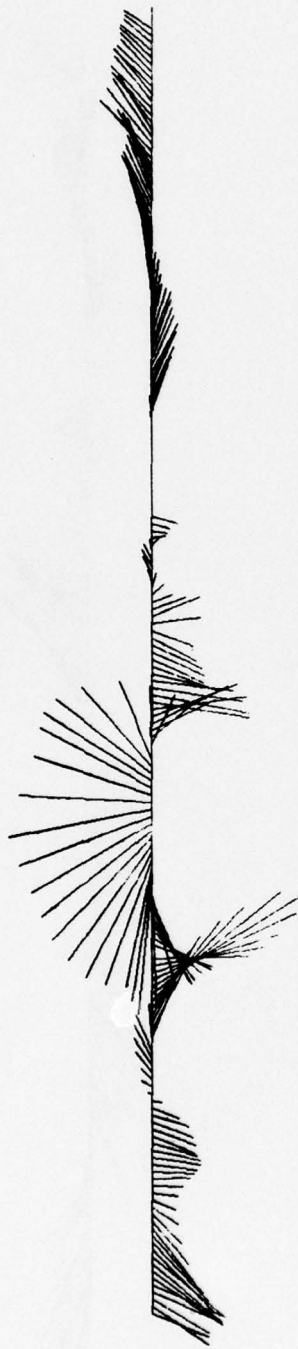
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JUL 7 14 21 28
AUG 7 14 21 28
SEP 7 14 21 28
OCT 7 14 21 28
NOV 7 14 21 28
DEC 7 14 21 28
1975 -- STUDY 49

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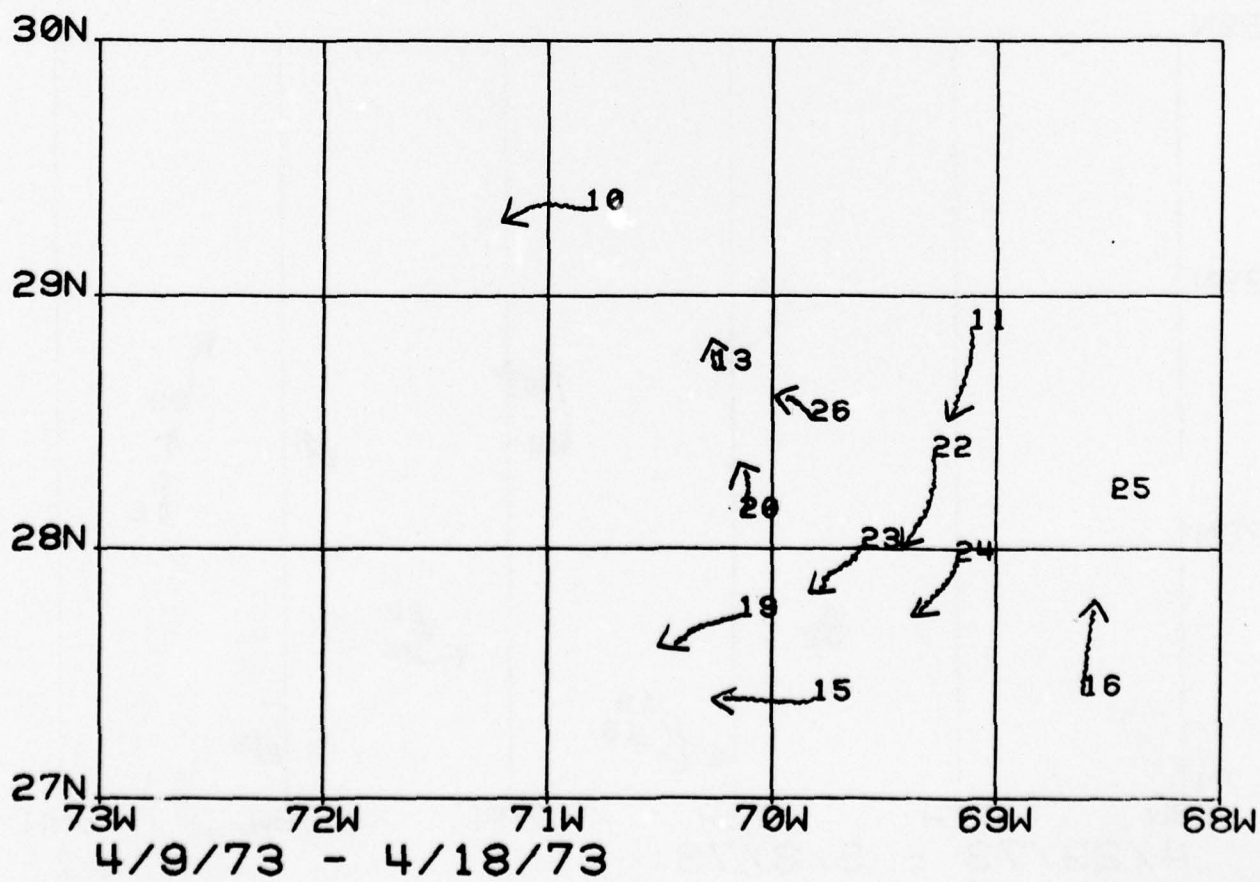
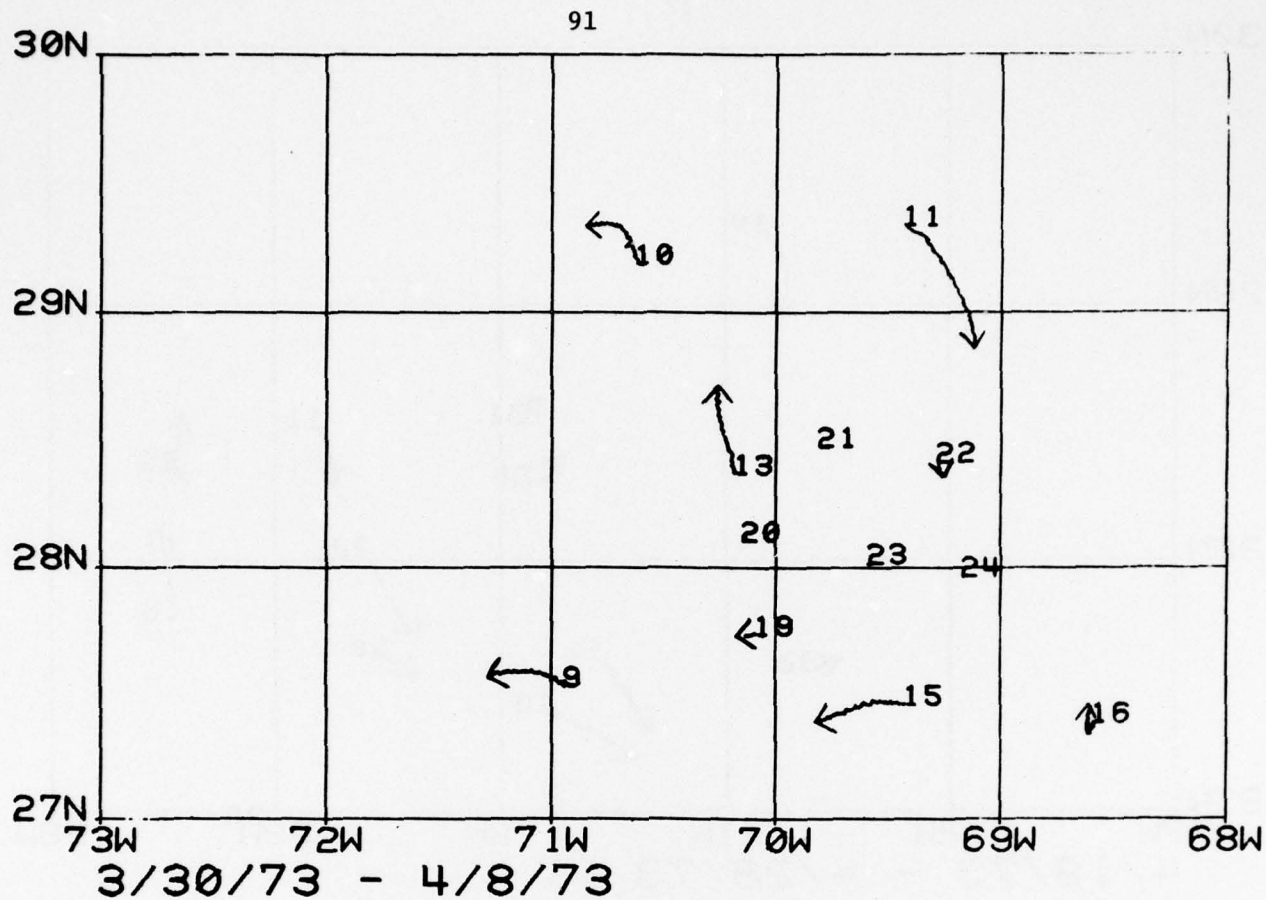
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FEB 7 14 21 28
MAR 7 14 21 28
APR 7 14 21 28
MAY 7 14 21 28
JUN 7 14 21 28
1976 -- STUDY 49

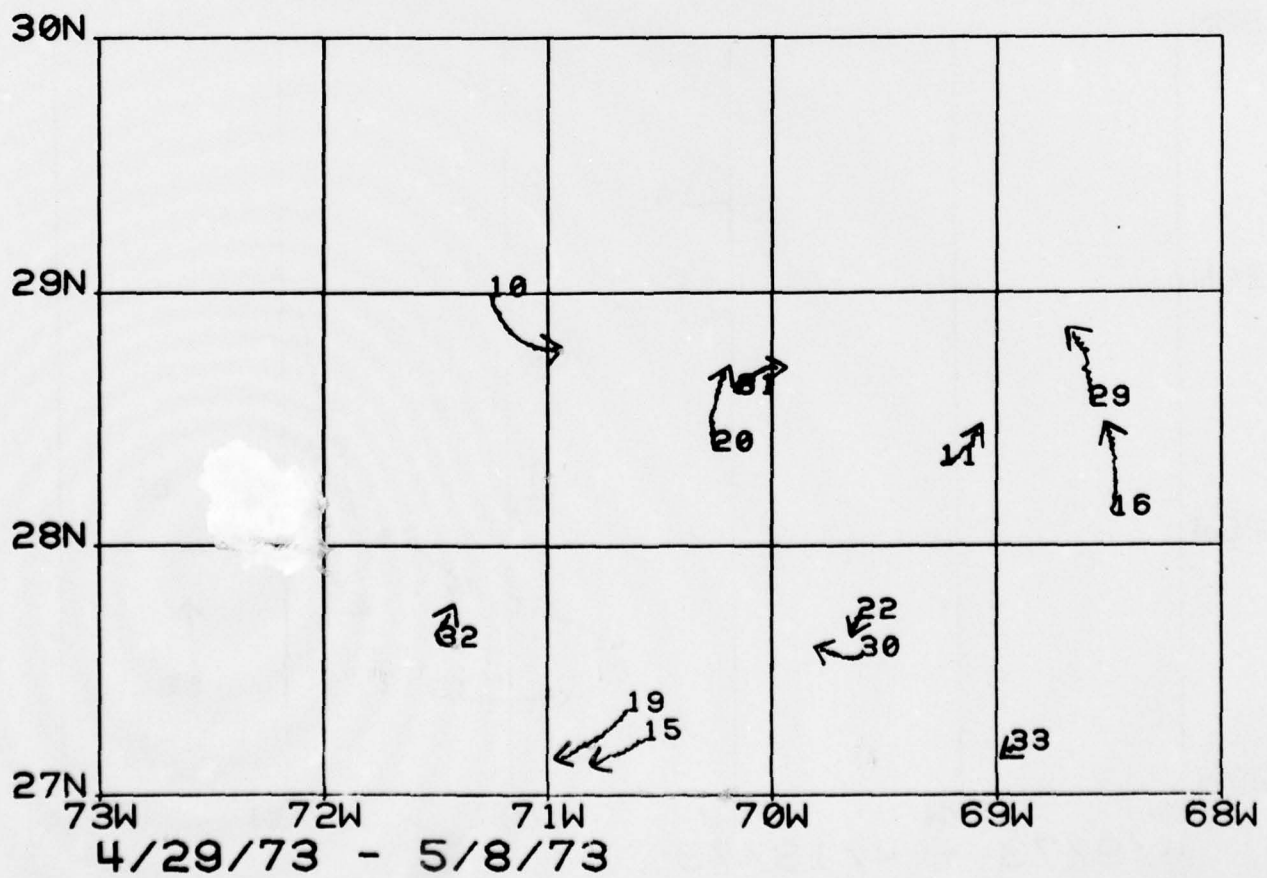
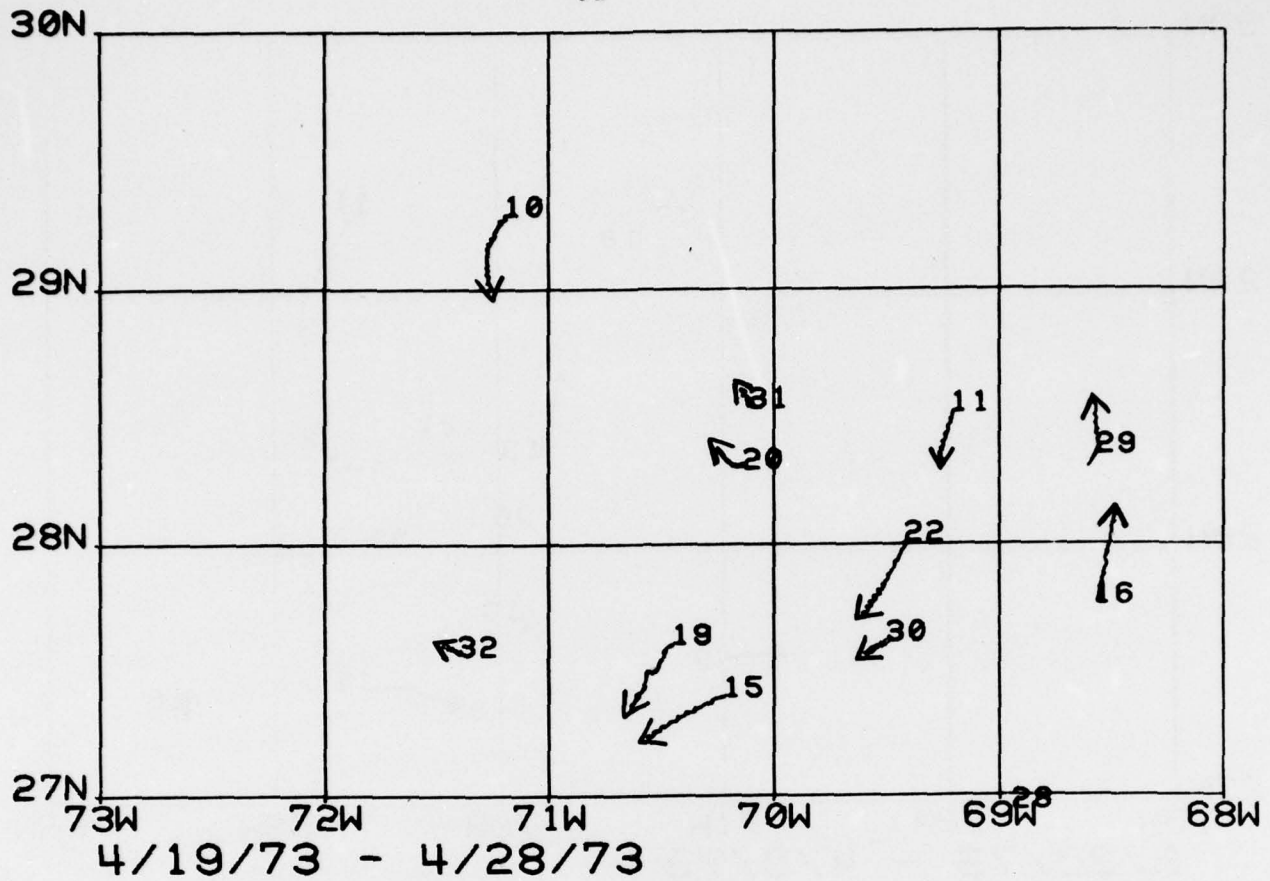
TEN DAY TRAJECTORIES

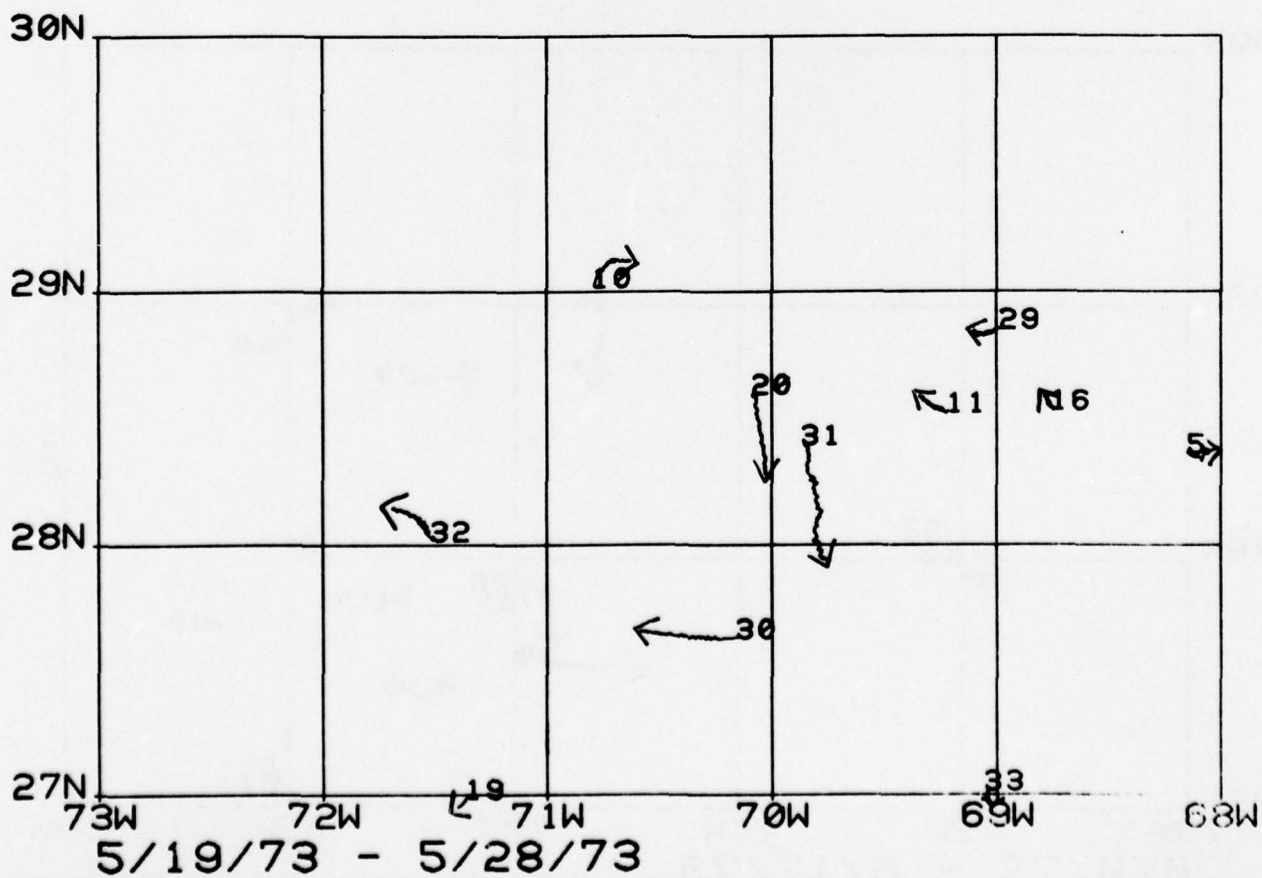
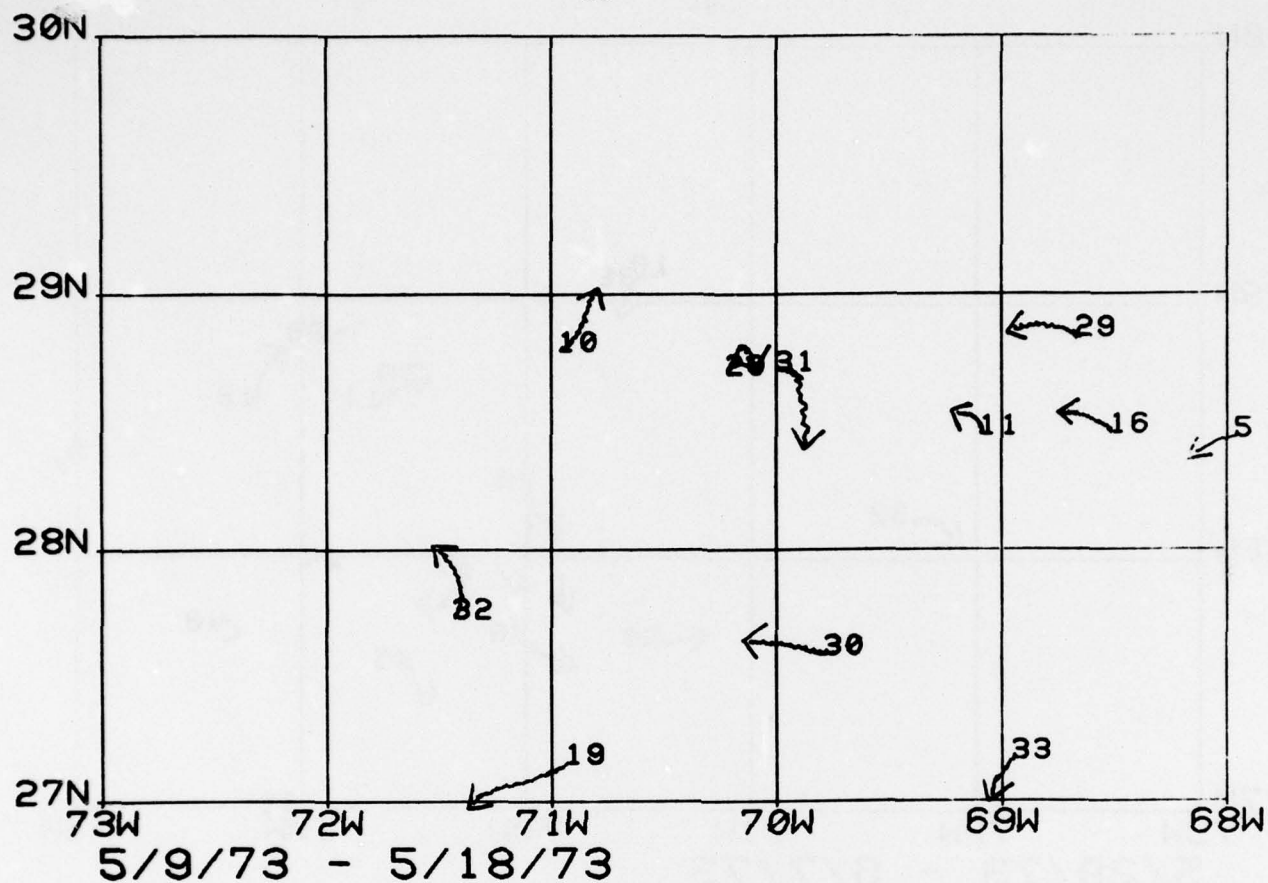
These charts cover the area 27°N-30°N and 73°W-68°W for the period April 1973 through January 1974. This area and time period were chosen to show the greatest number of floats in a small area so the relative motion of floats over small time periods could easily be seen. The study number shows the position of the float on the first day of the ten day period. If the float was launched during the ten day period, the study number shows the launch position. The position of the float at the end of the ten day period, or at recovery or failure, is shown by an arrowhead indicating the general direction of drift. Table 1 gives launch and recovery information and is intended for use in conjunction with these charts.

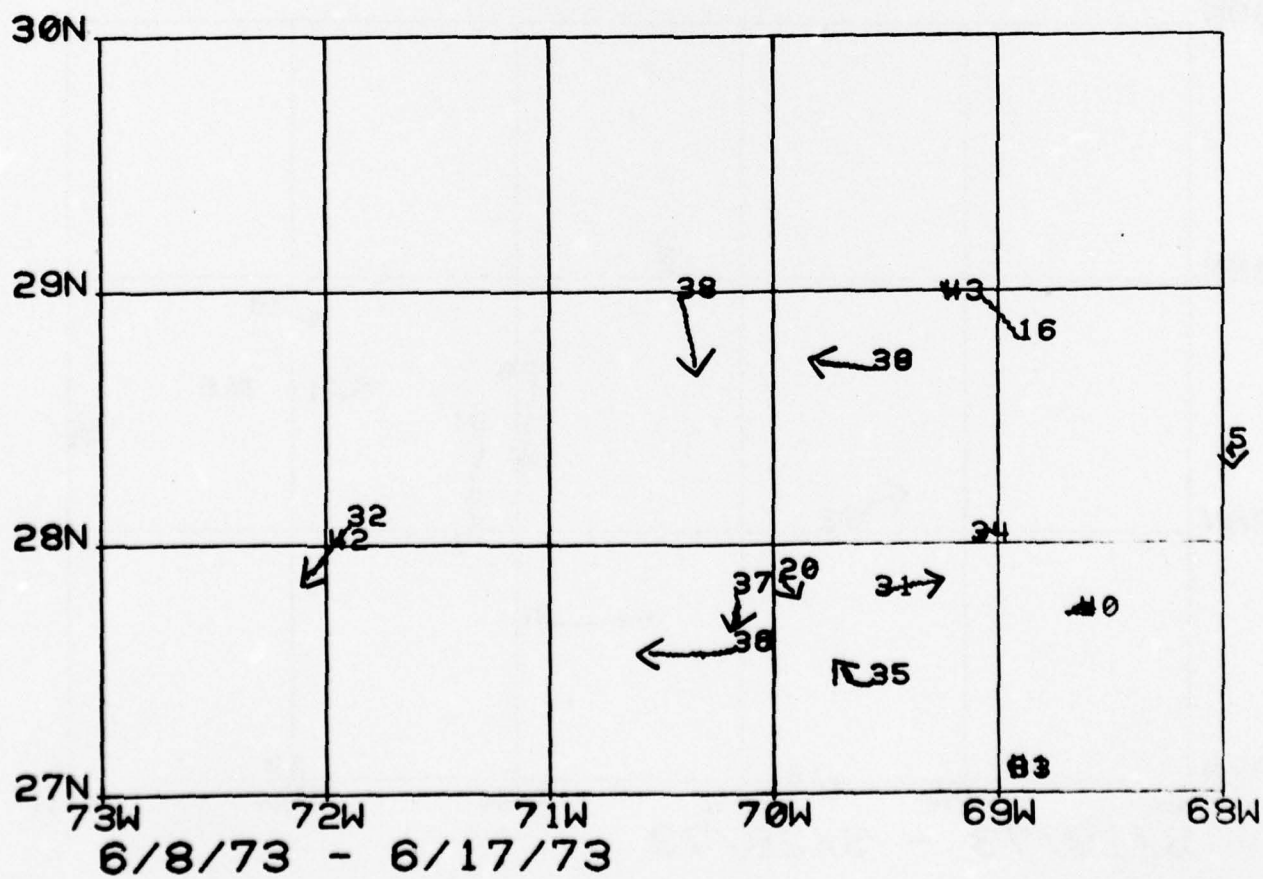
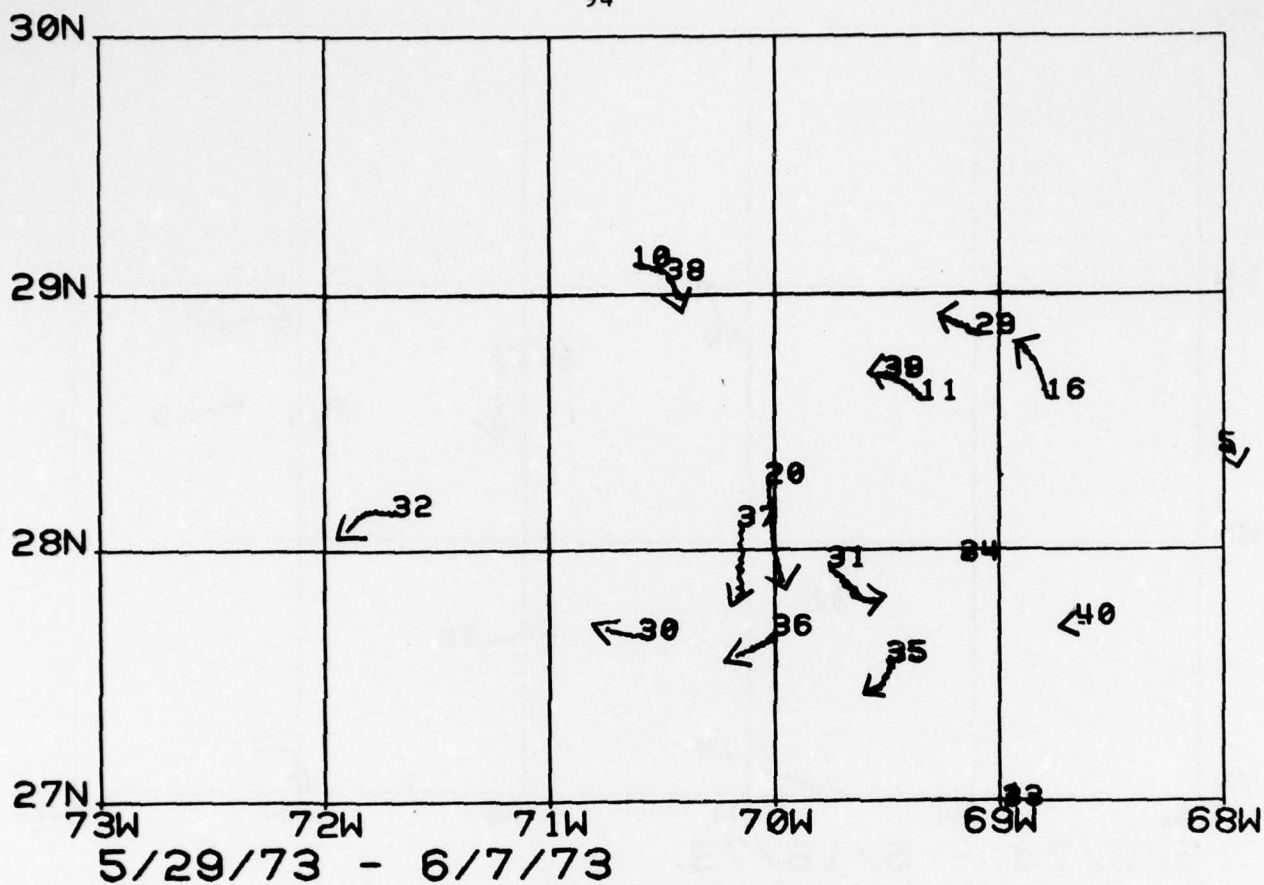
Positions are plotted six times a day. No smoothing or filtering has been done on these positions. Wiggles on the trajectories which occur at regular intervals are due to inertial oscillations, and those which are irregular are due to errors in TOA calculation, which, in this area, are usually caused by a weak float signal.

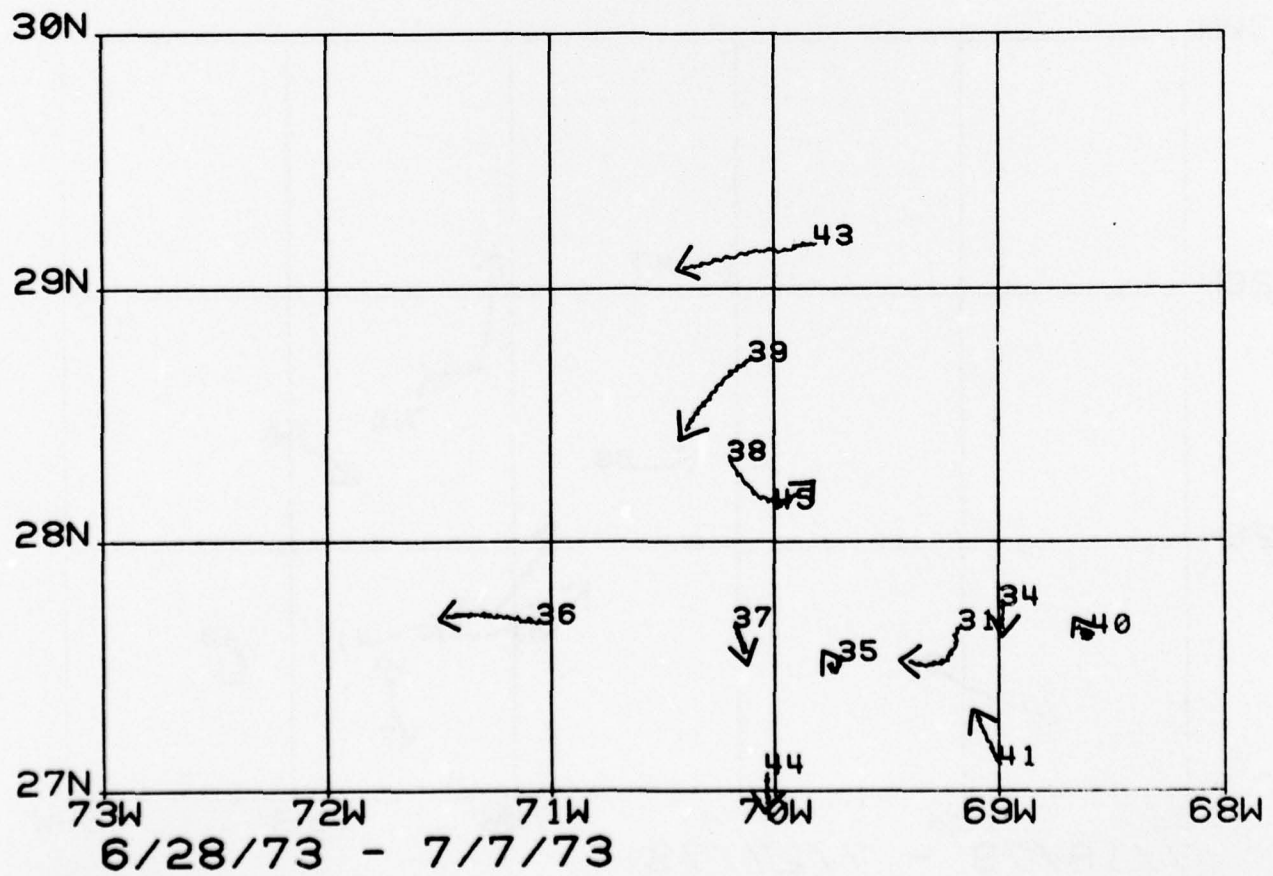
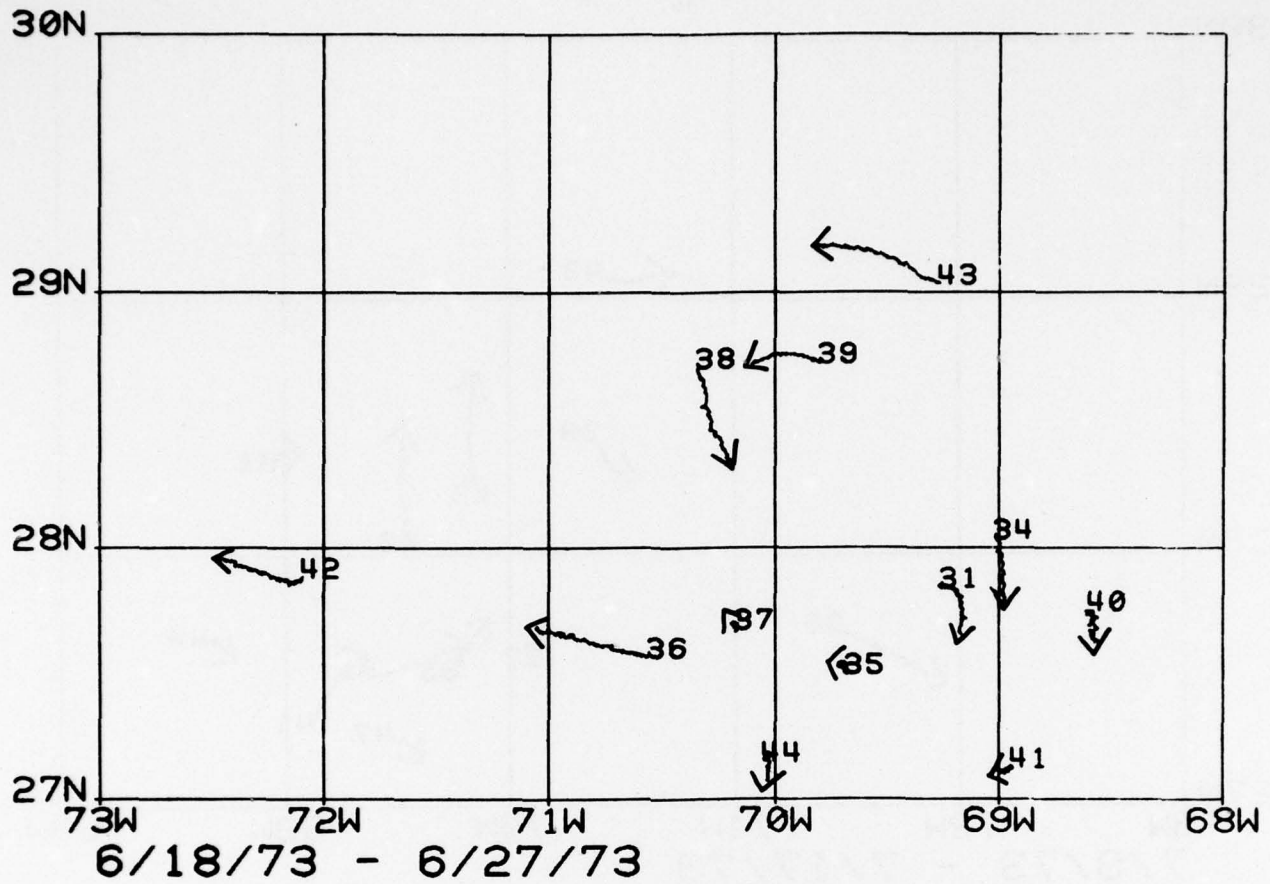
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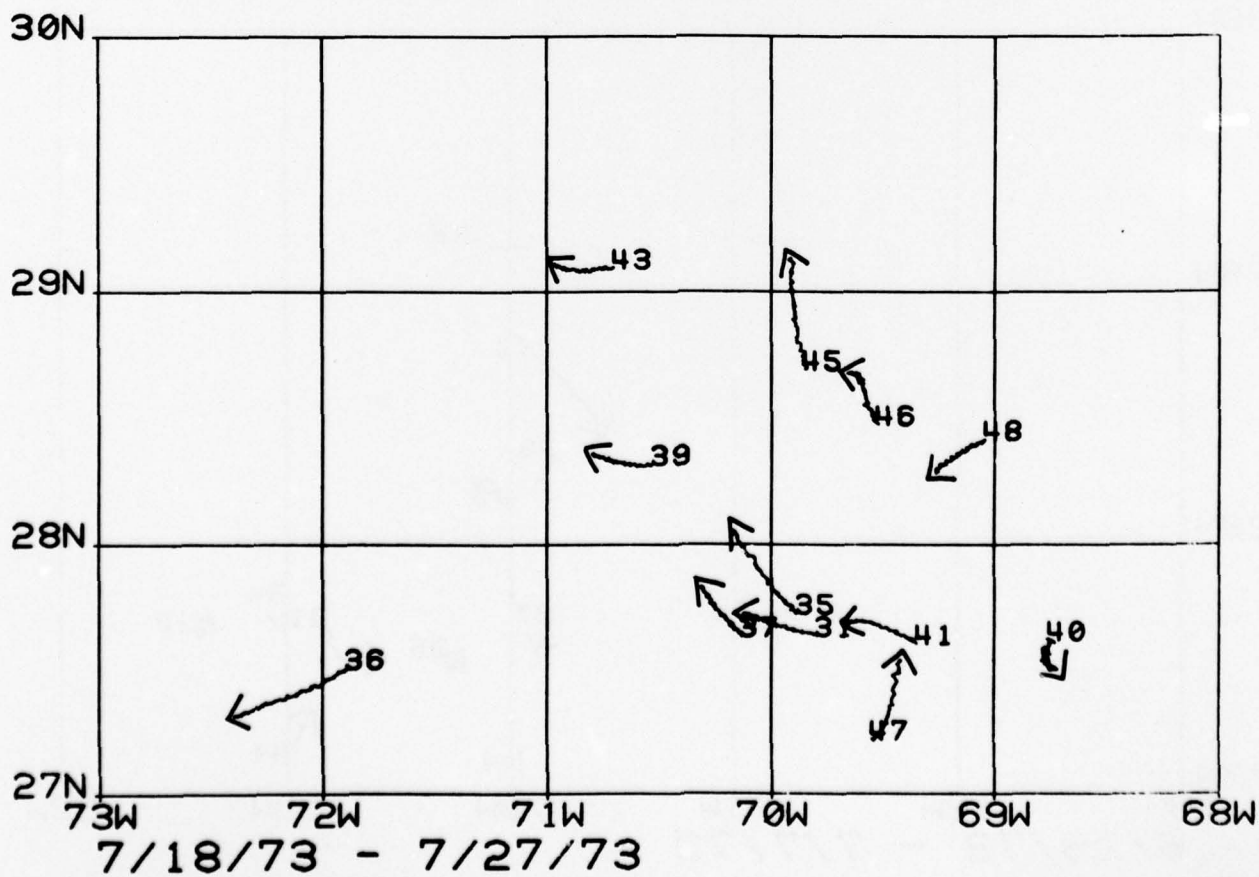
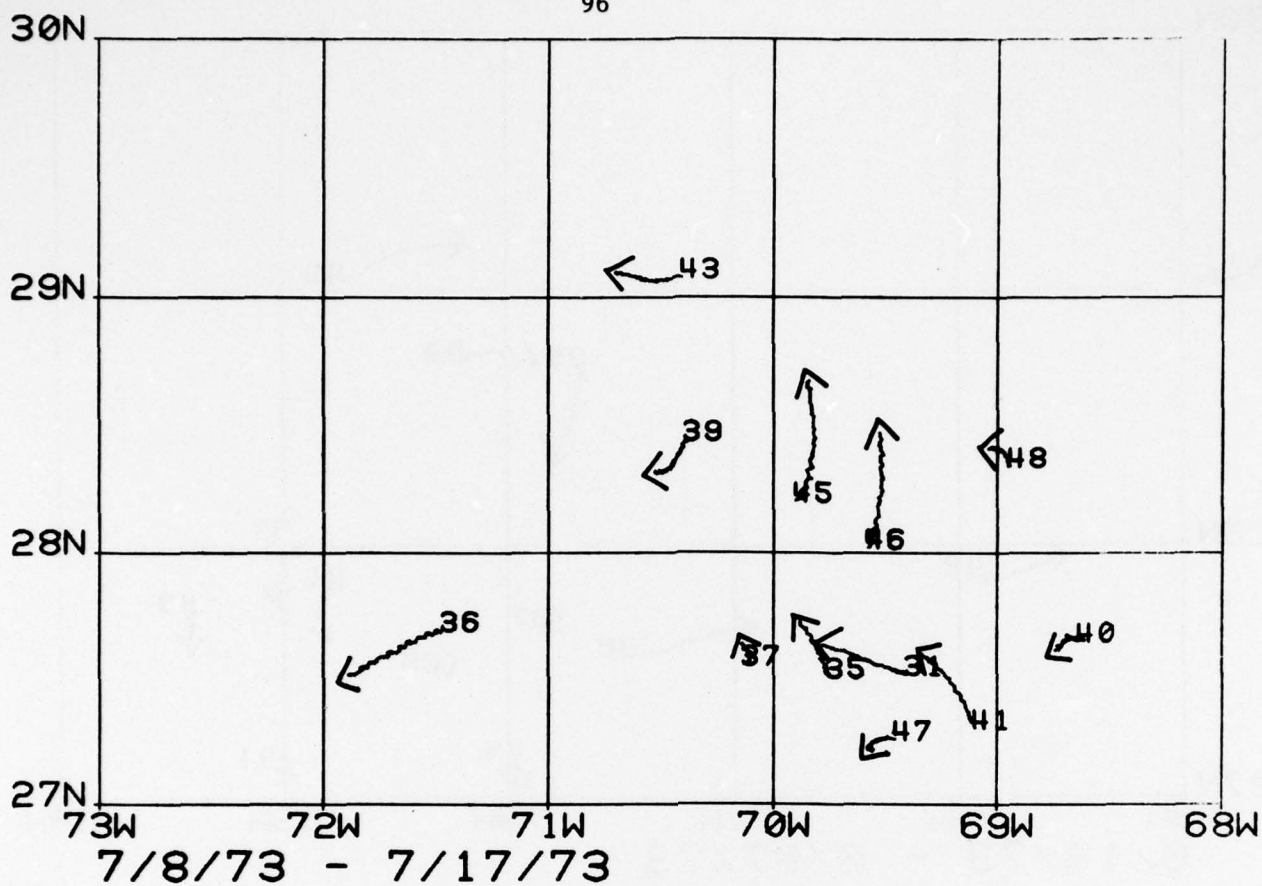


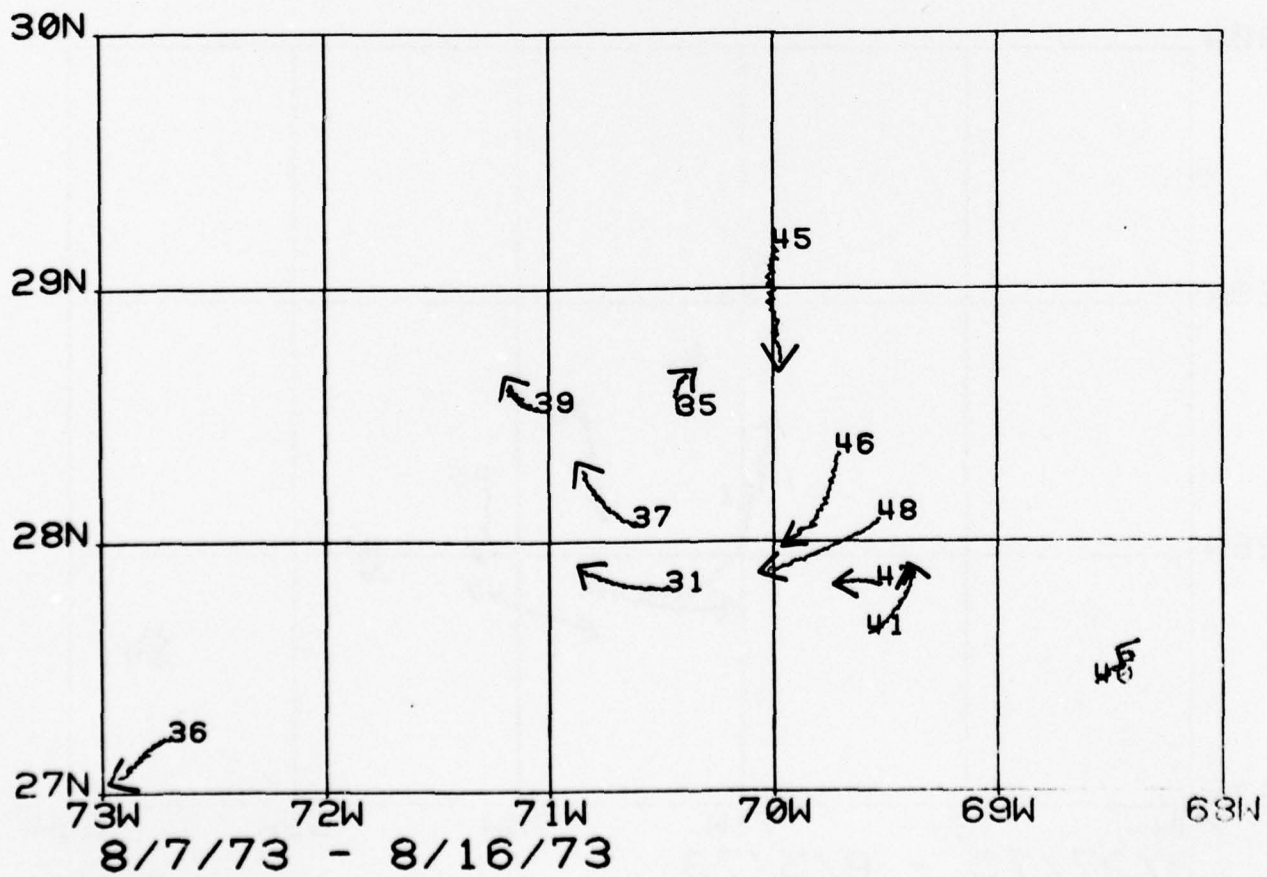
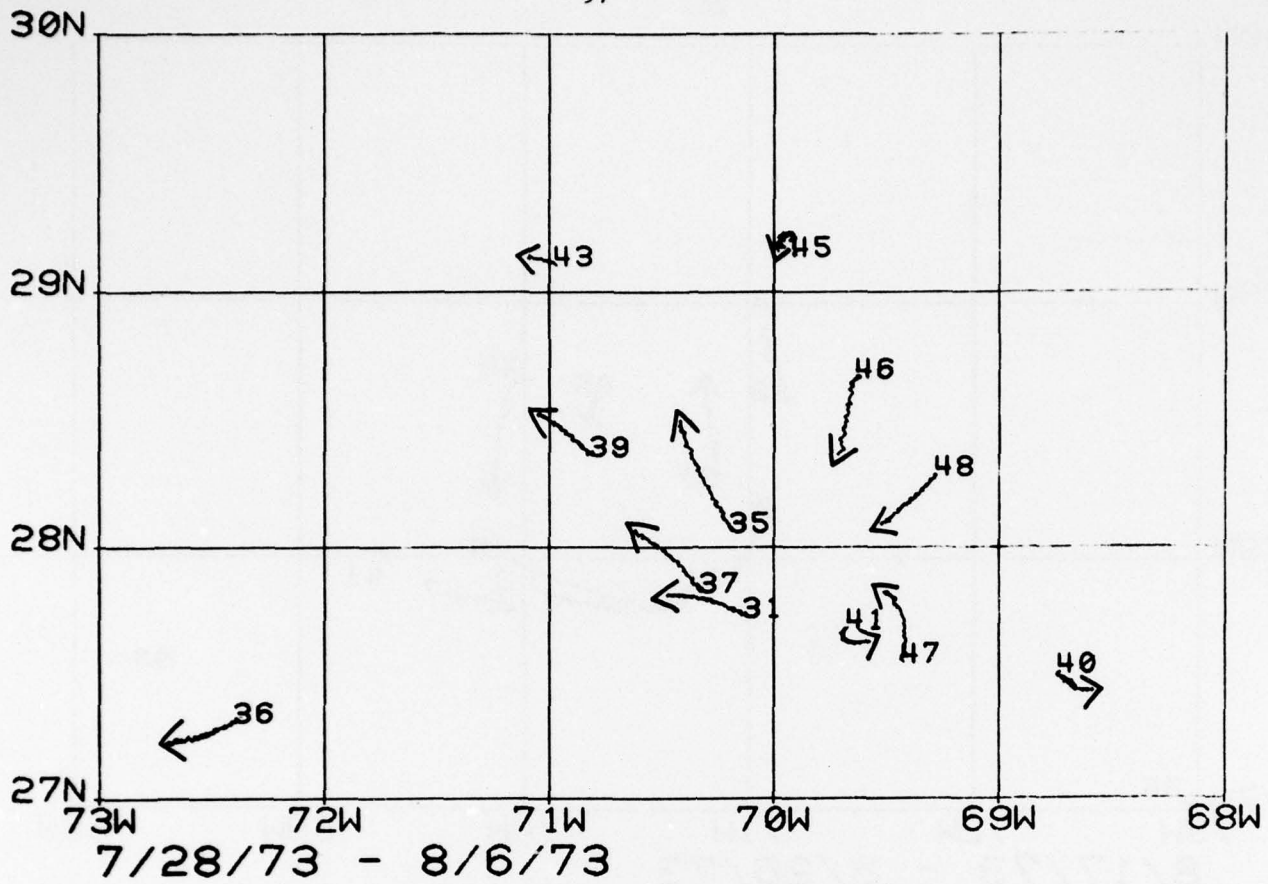


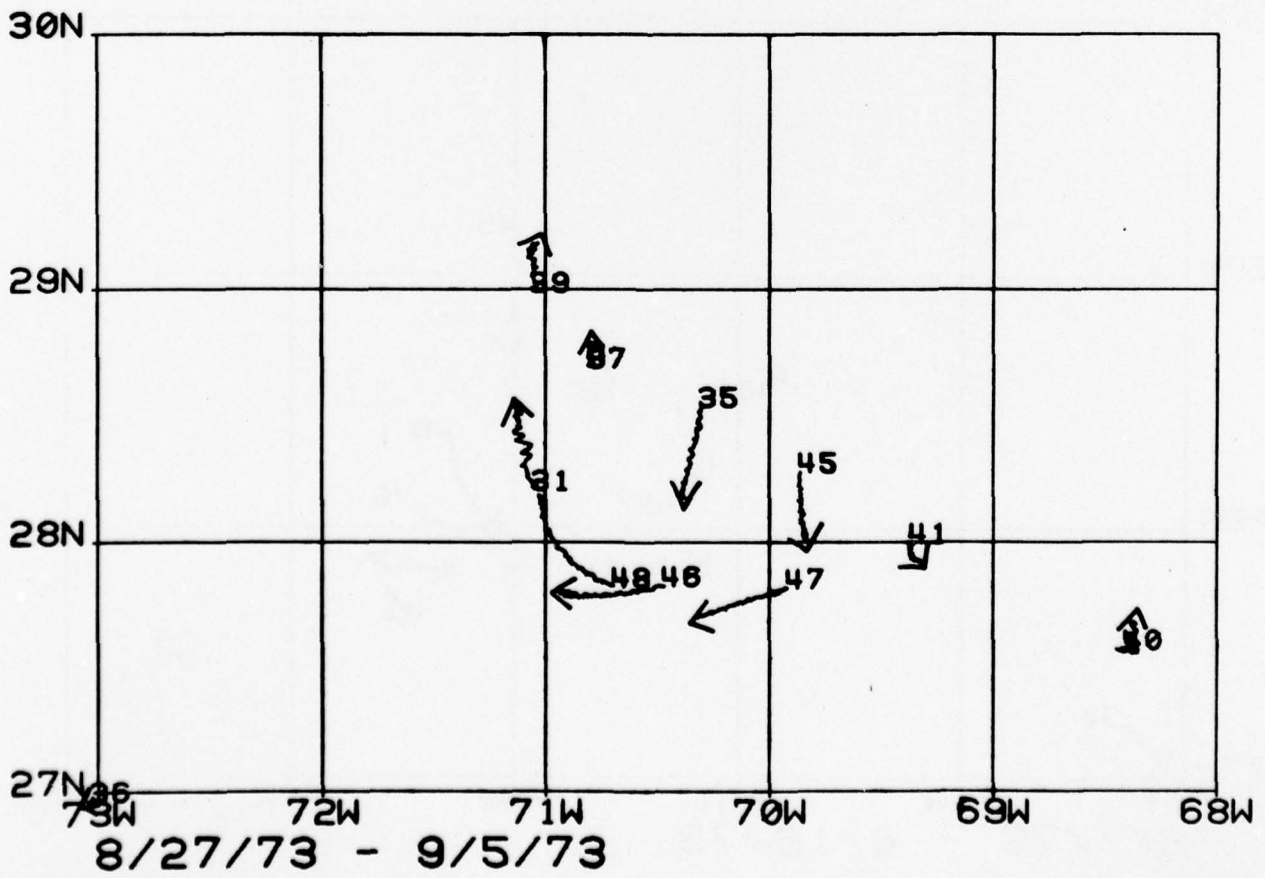
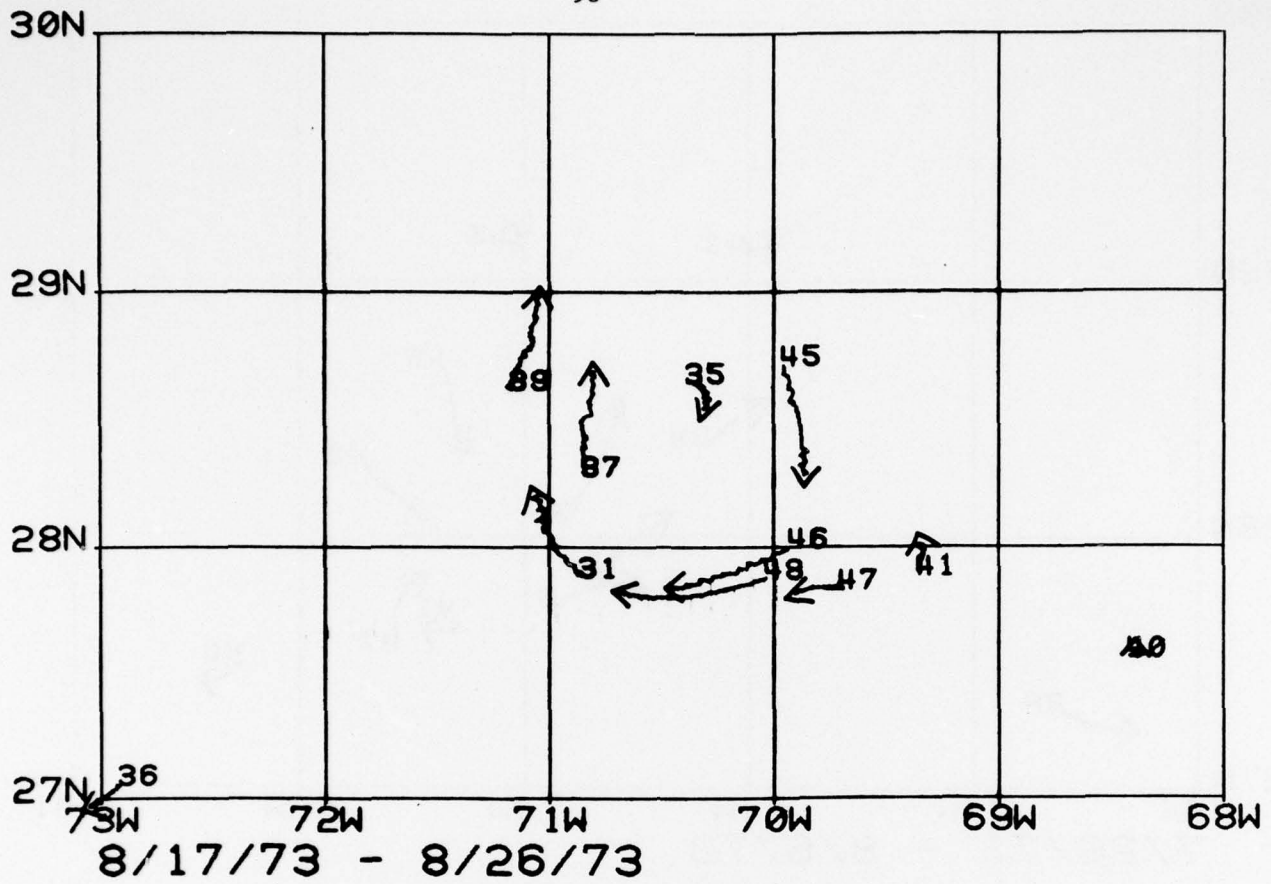


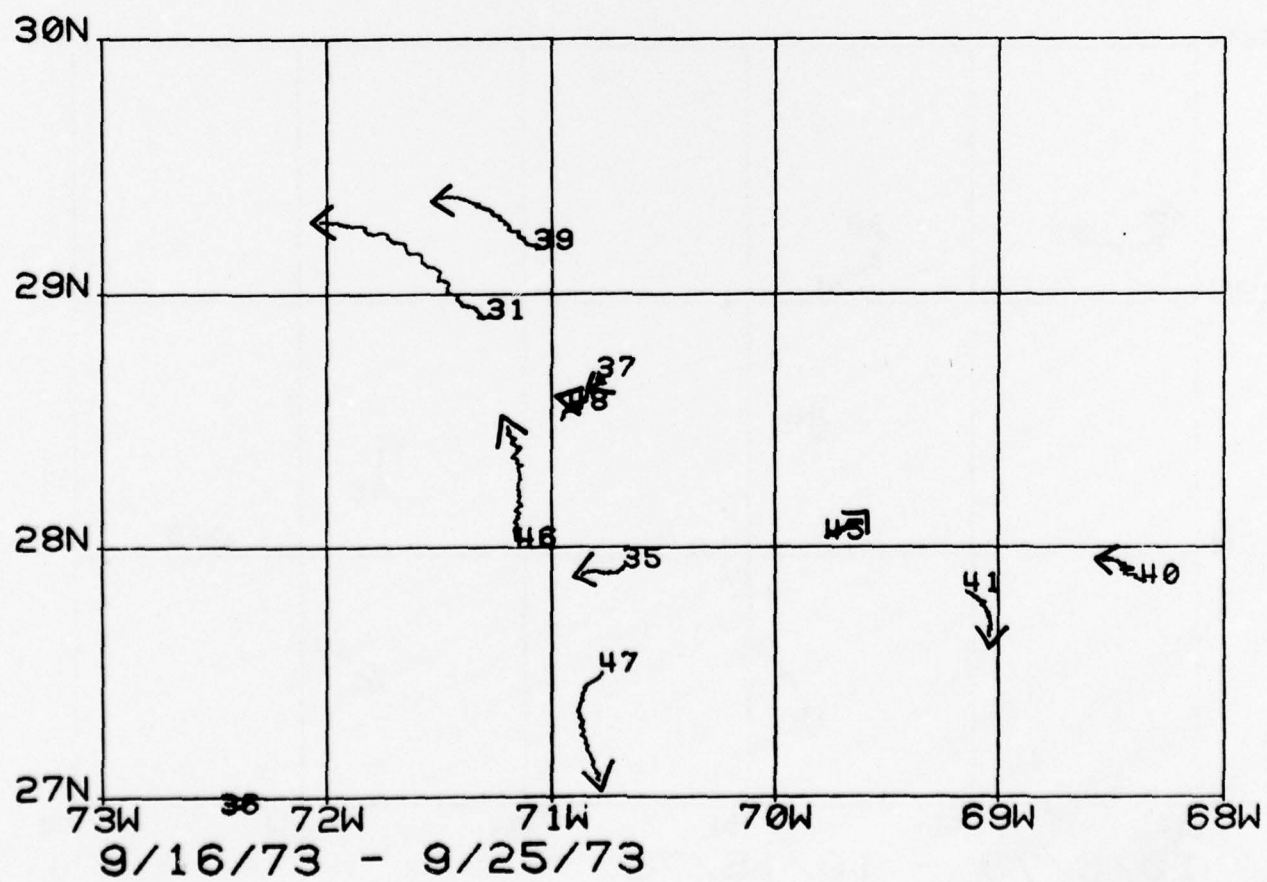


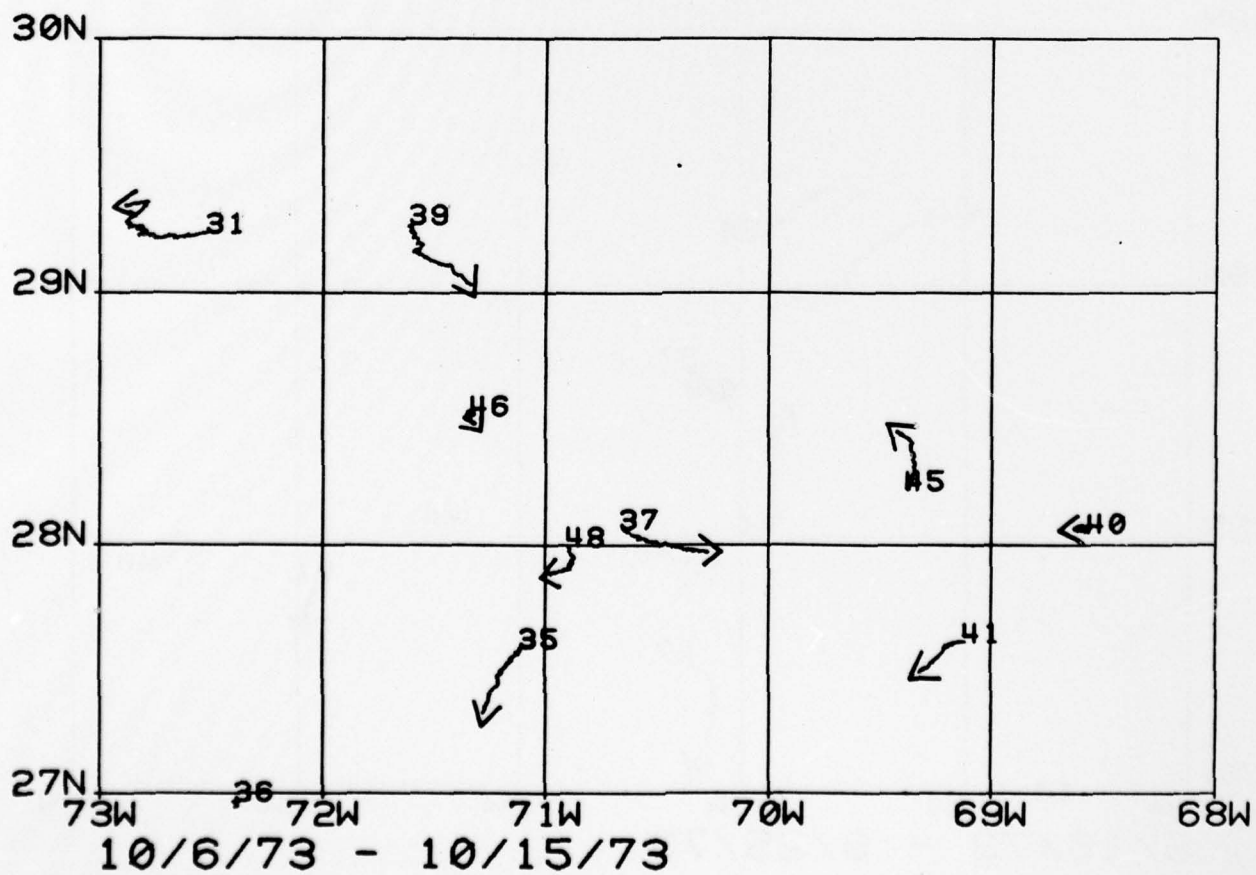
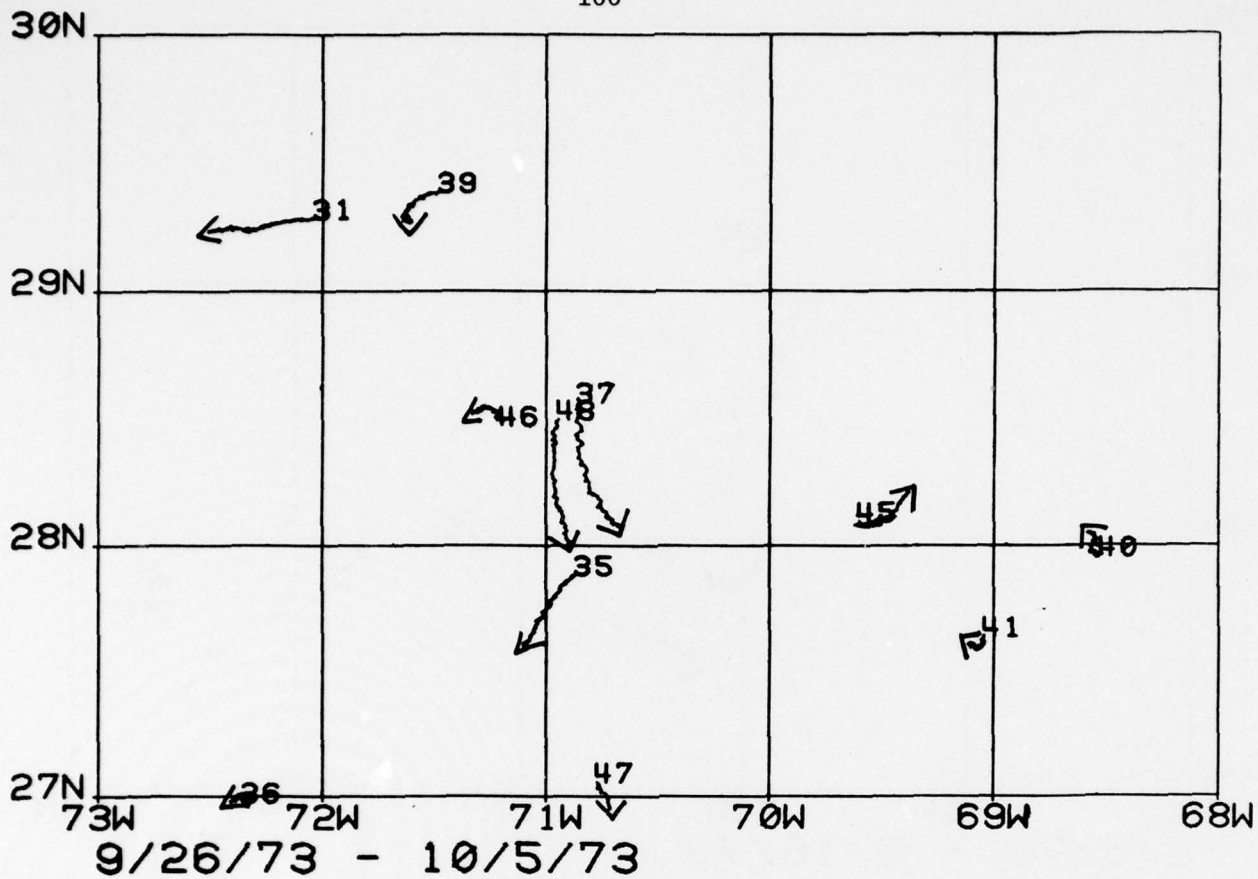


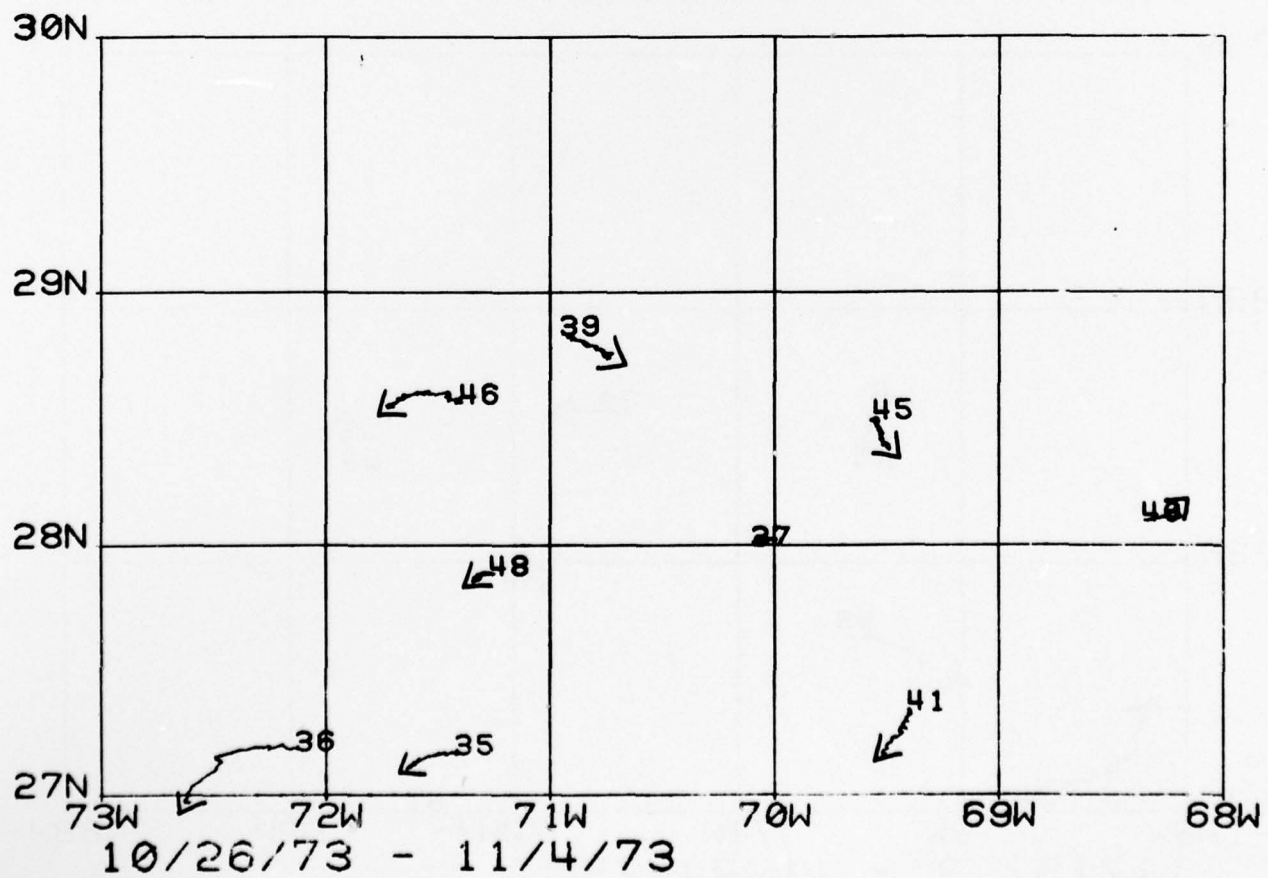
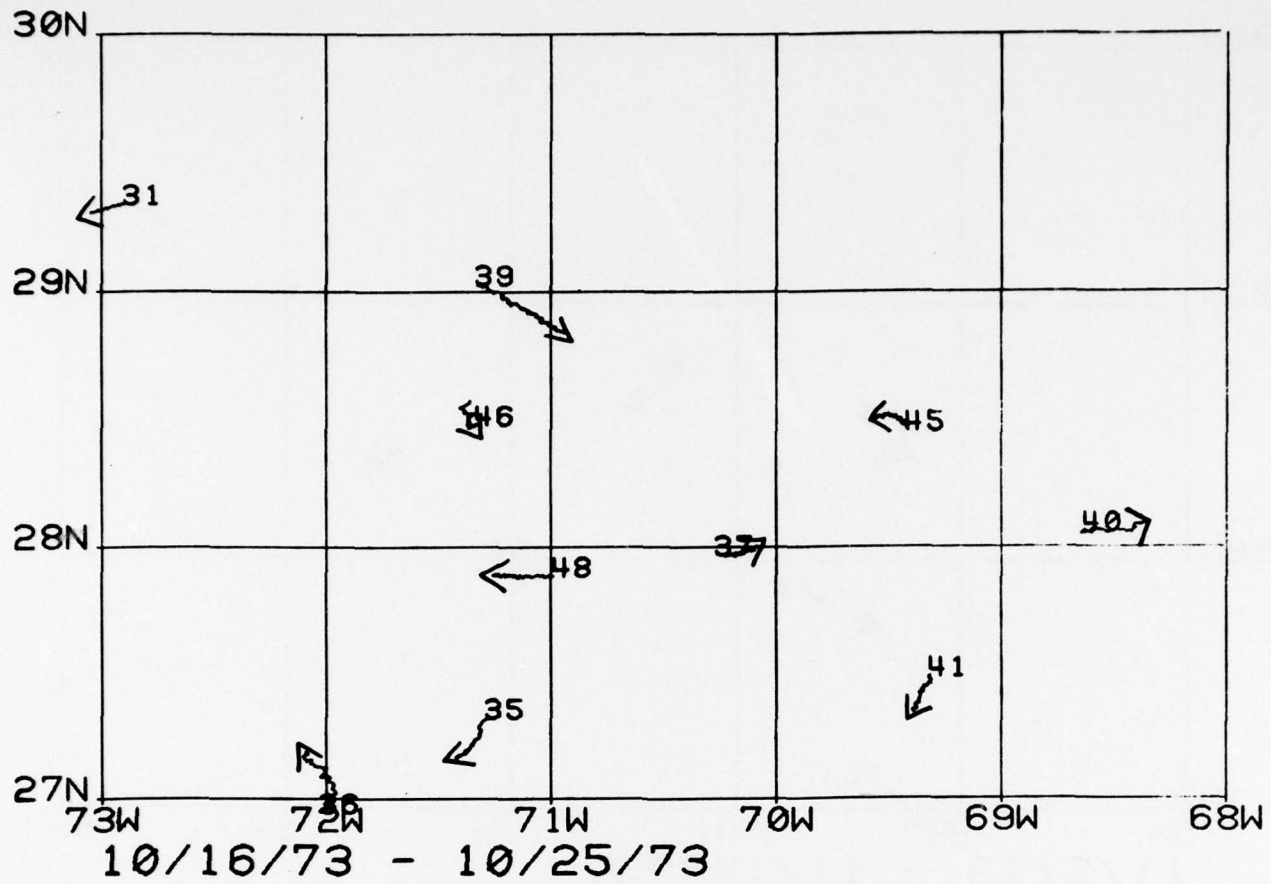


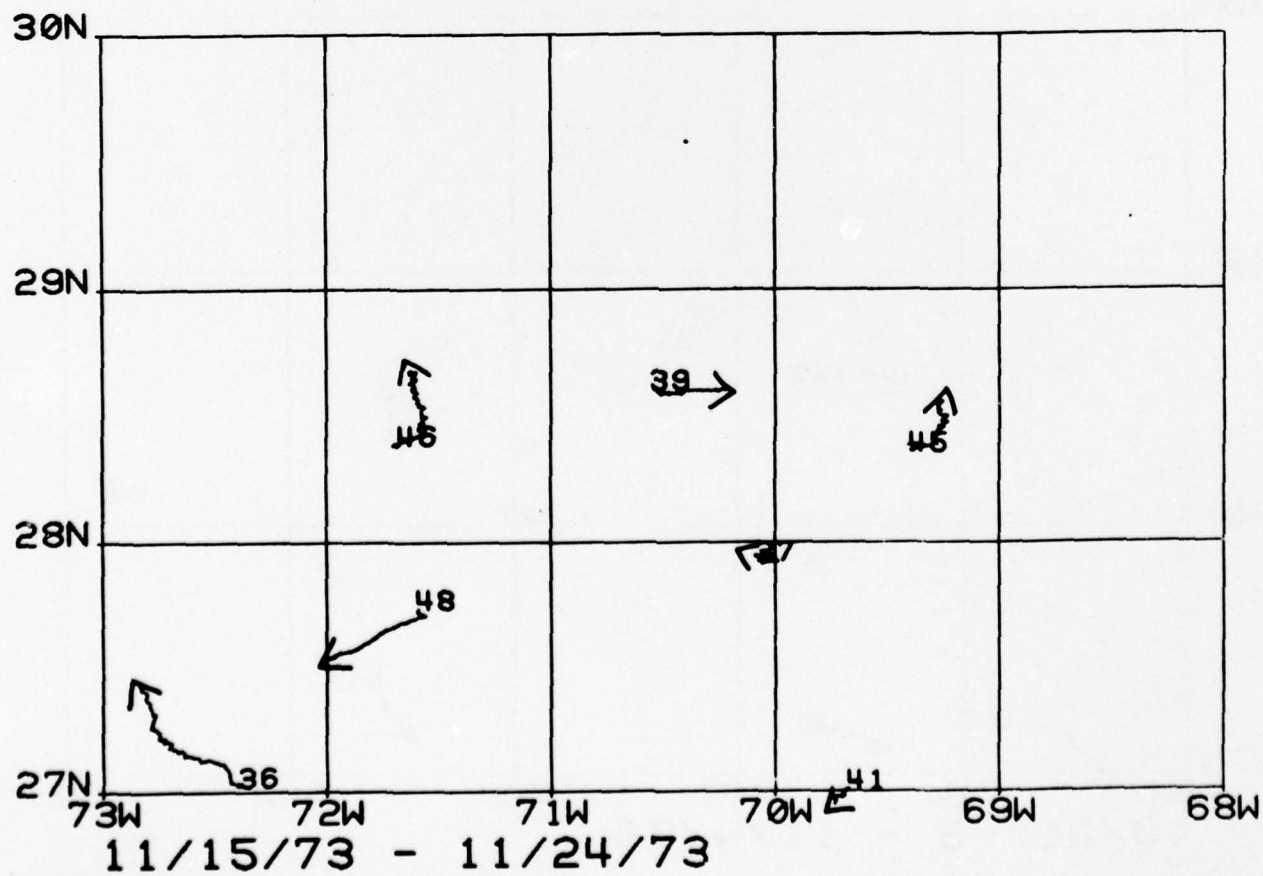
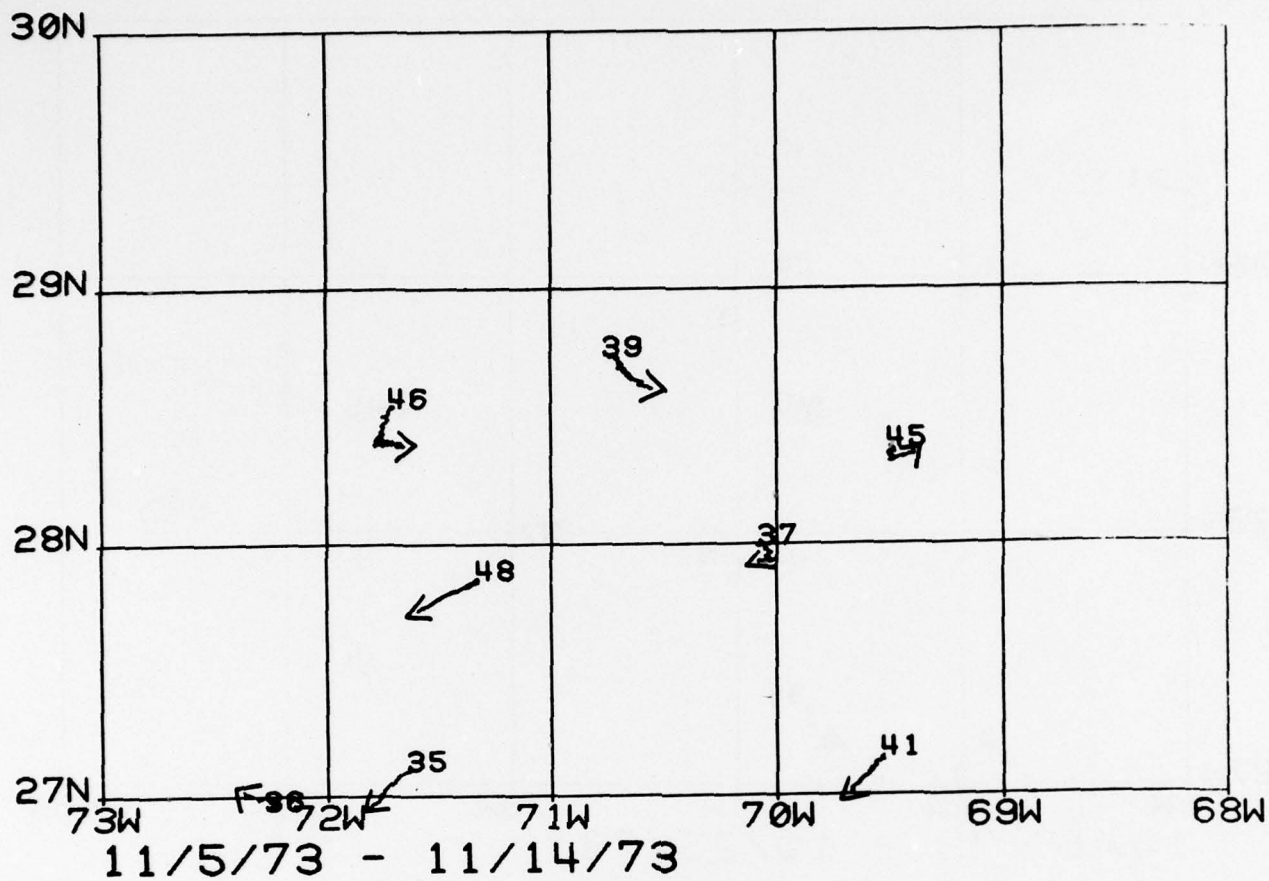


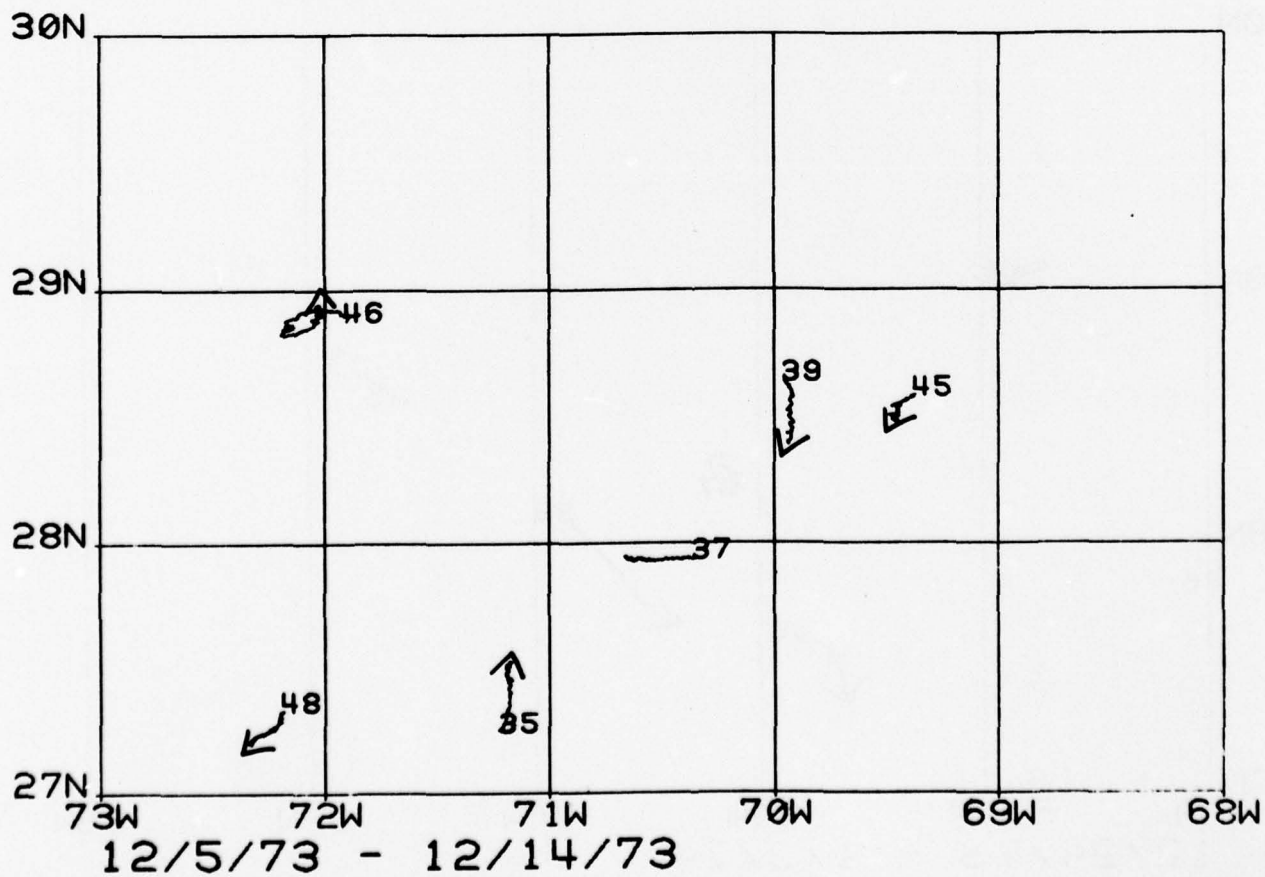
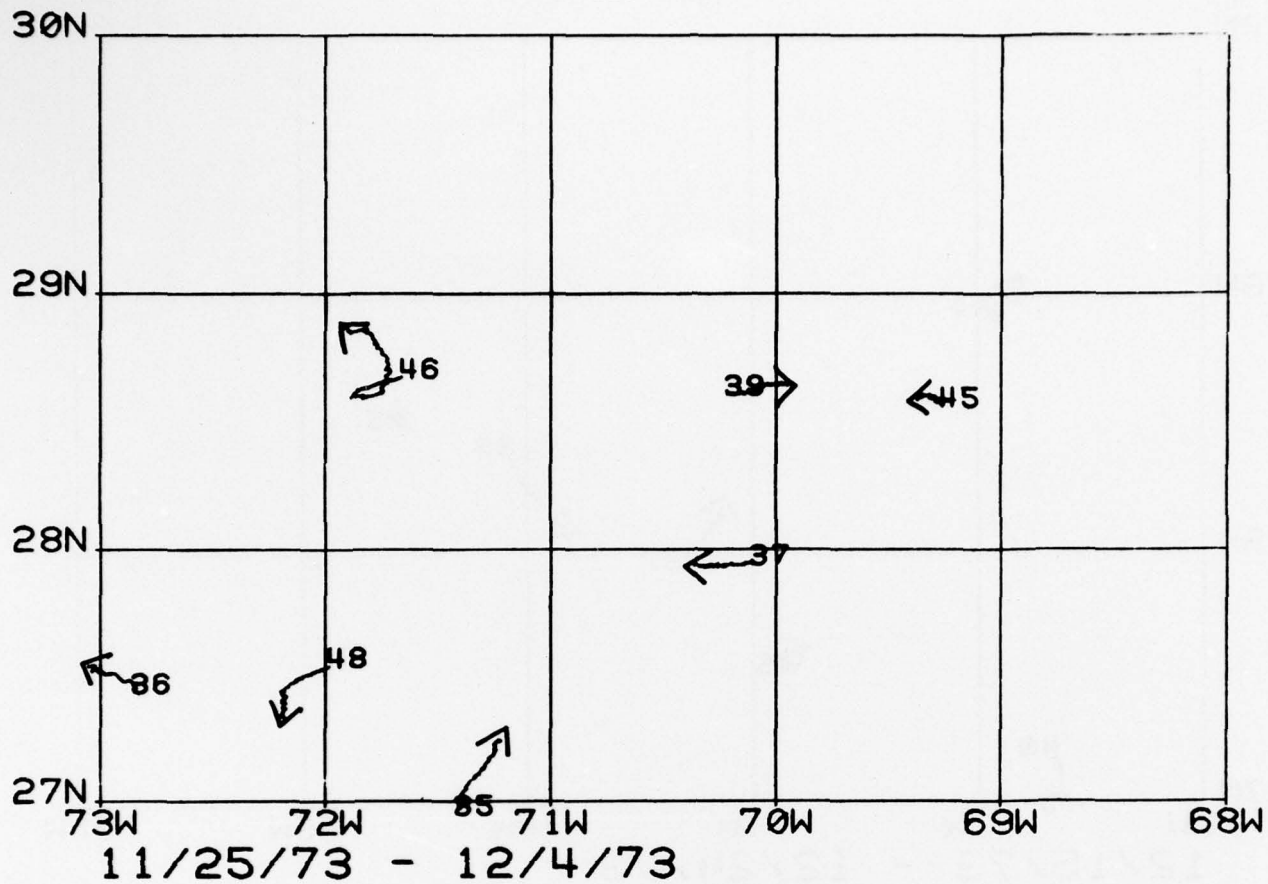


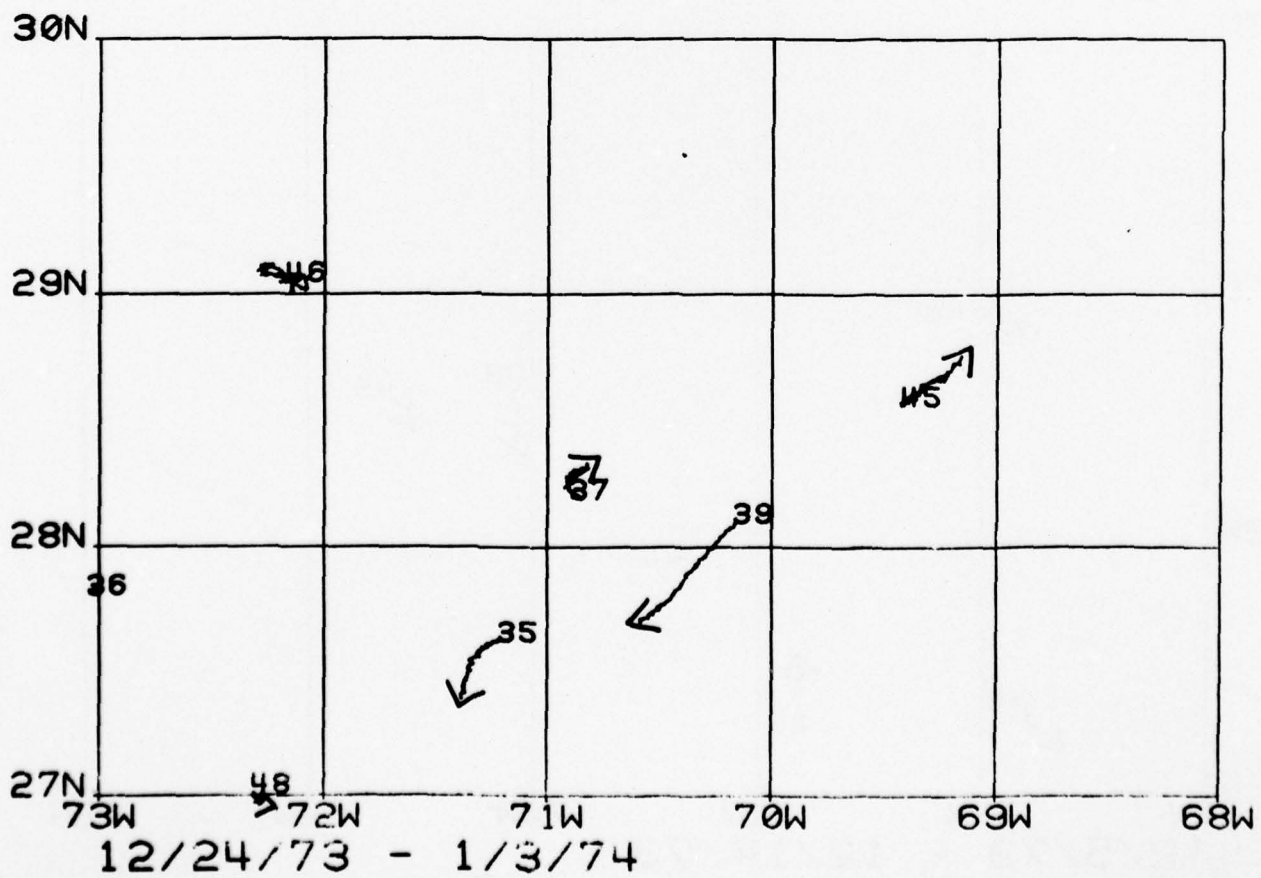
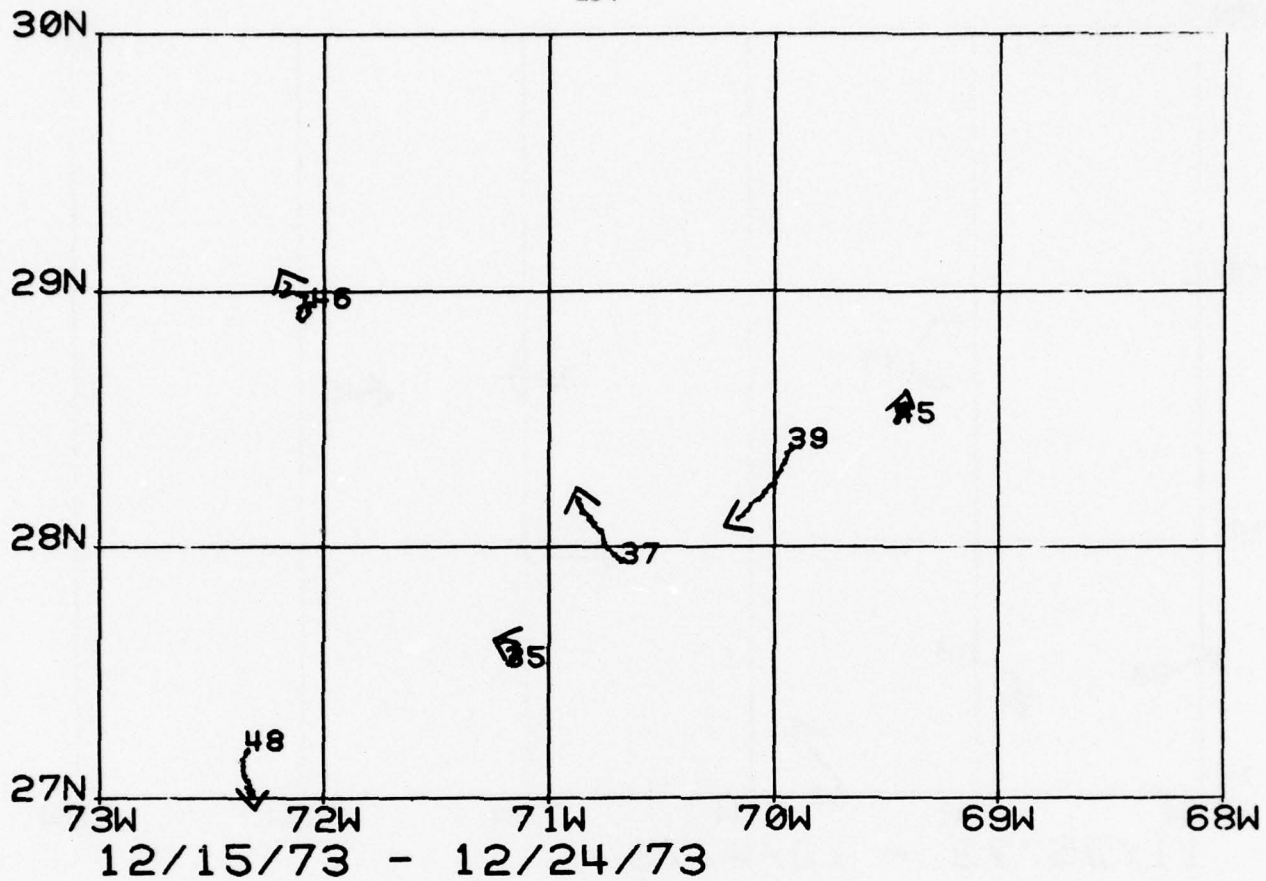


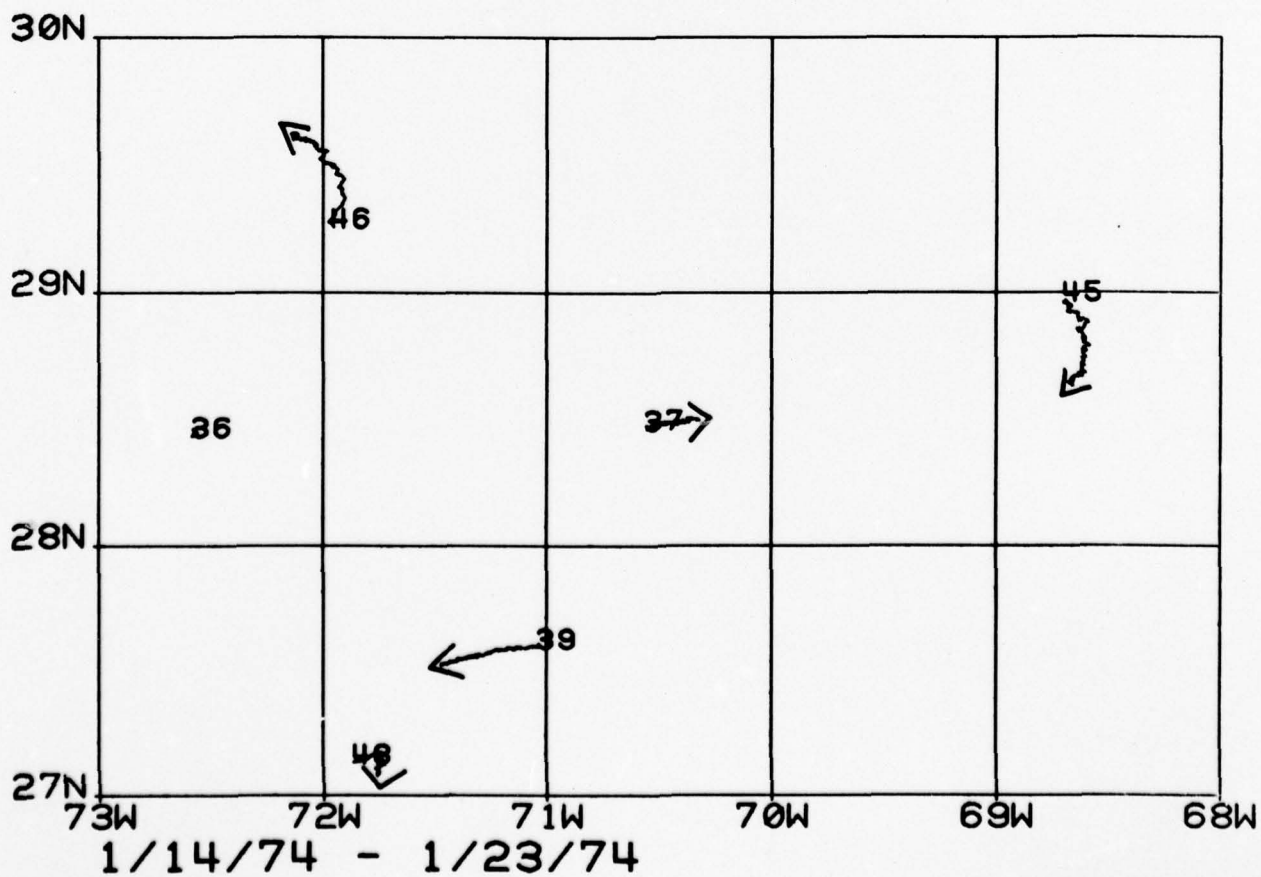
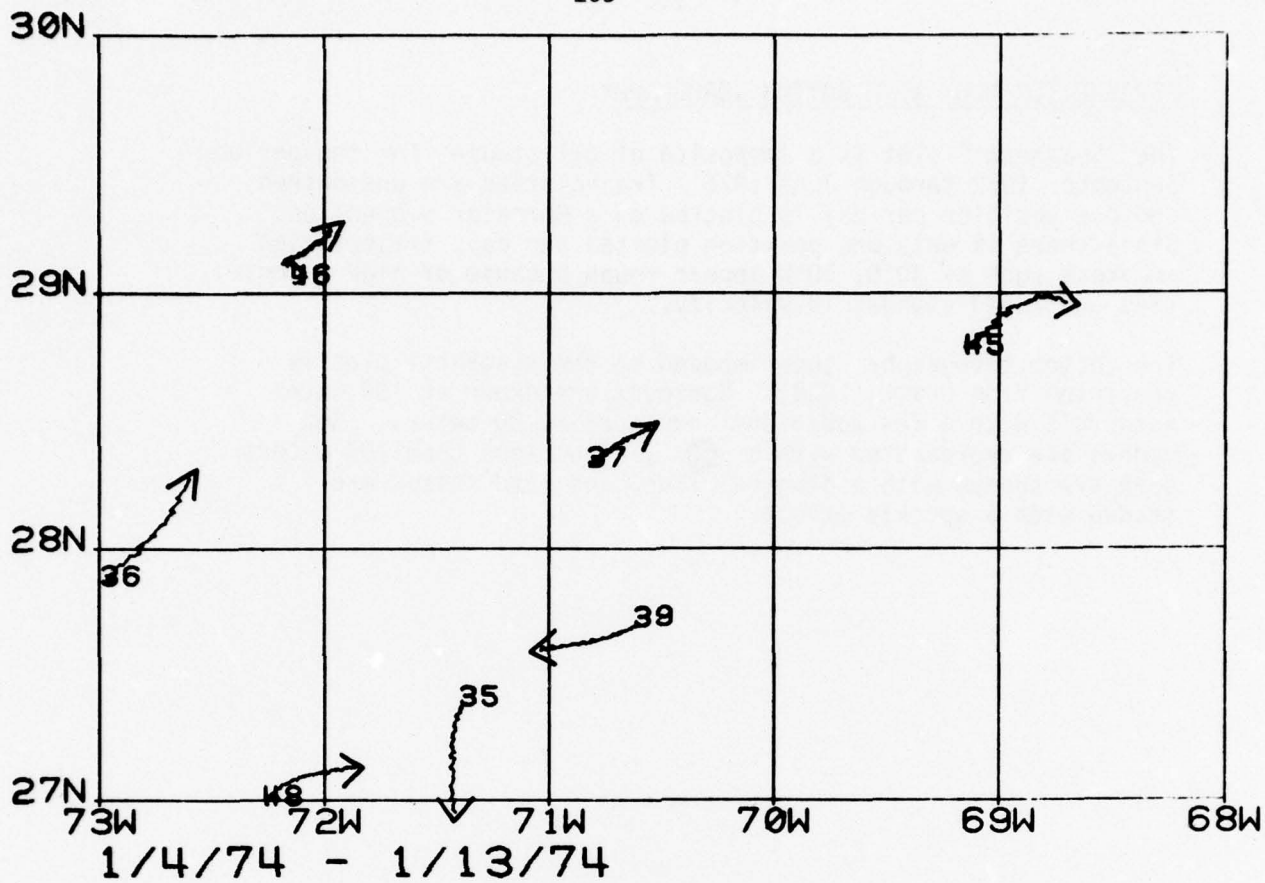













"SPAGHETTI" PLOT WITH BOTTOM TOPOGRAPHY

The "Spaghetti" plot is a composite of all studies for the period September 1972 through June 1976. Trajectories are unsmoothed and one position per day is plotted on a Mercator projection. Since there is only one position plotted per day, trajectories in areas such as 30°N, 70°W appear rough because of high velocities and rapid changes in velocity.

The bottom topography, superimposed on the spaghetti plot is reprinted from Pratt (1968). Contours are drawn at 100 meter intervals with a few additional contours at 50 meters. Sea mounts are represented with a , areas less than 100 meters deep are shaded with a diagonal line, and land masses are shaded with a speckle effect.

ACKNOWLEDGMENTS

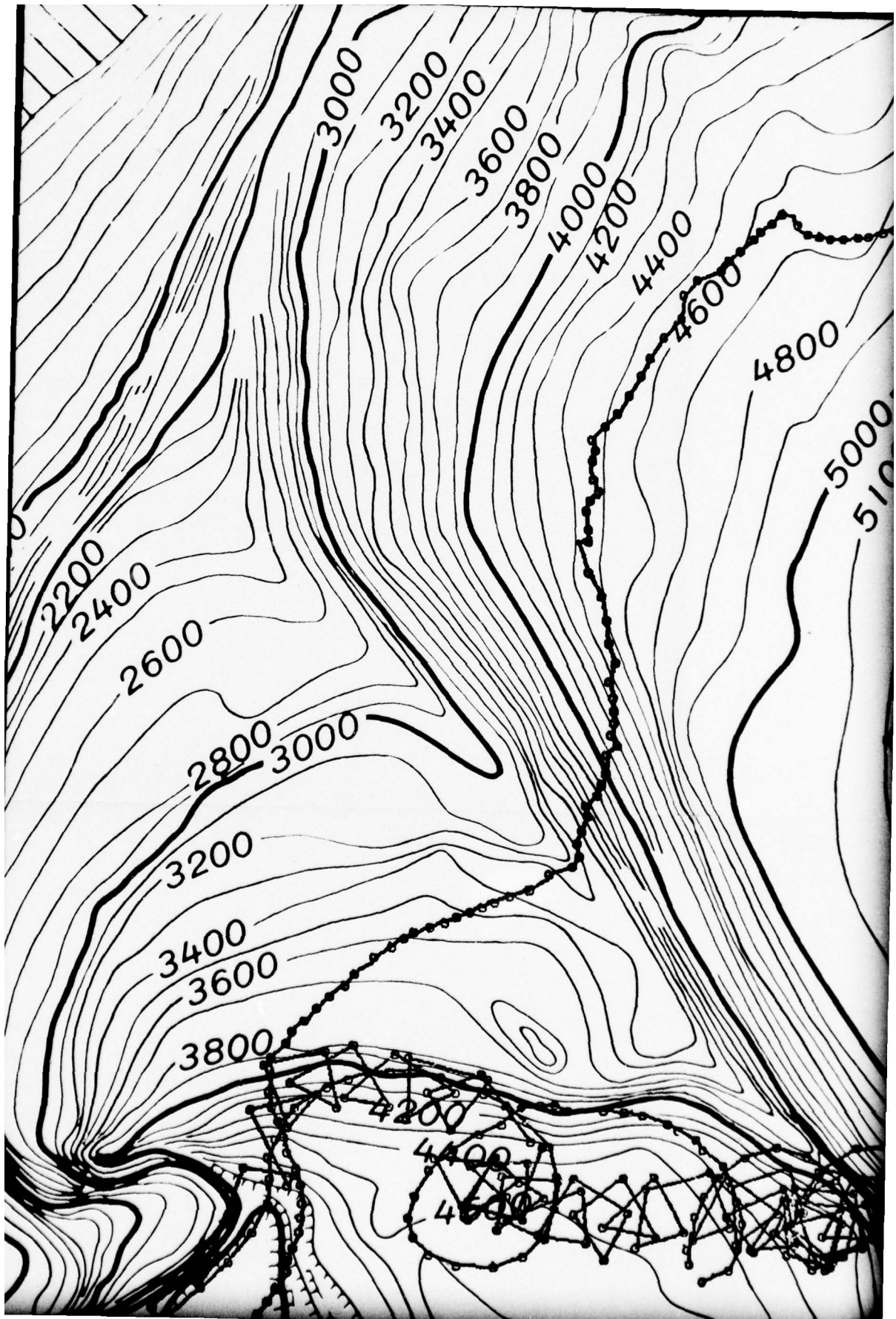
The SOFAR float program in MODE was truly the combined effort of many people. The instruments were designed and built by Mr. Douglas Webb and his engineering group at the Woods Hole Oceanographic Institution. We are grateful to the officers and crew of the NOAA vessel R/V RESEARCHER (OSS 03), who handled all the operations at sea during MODE.

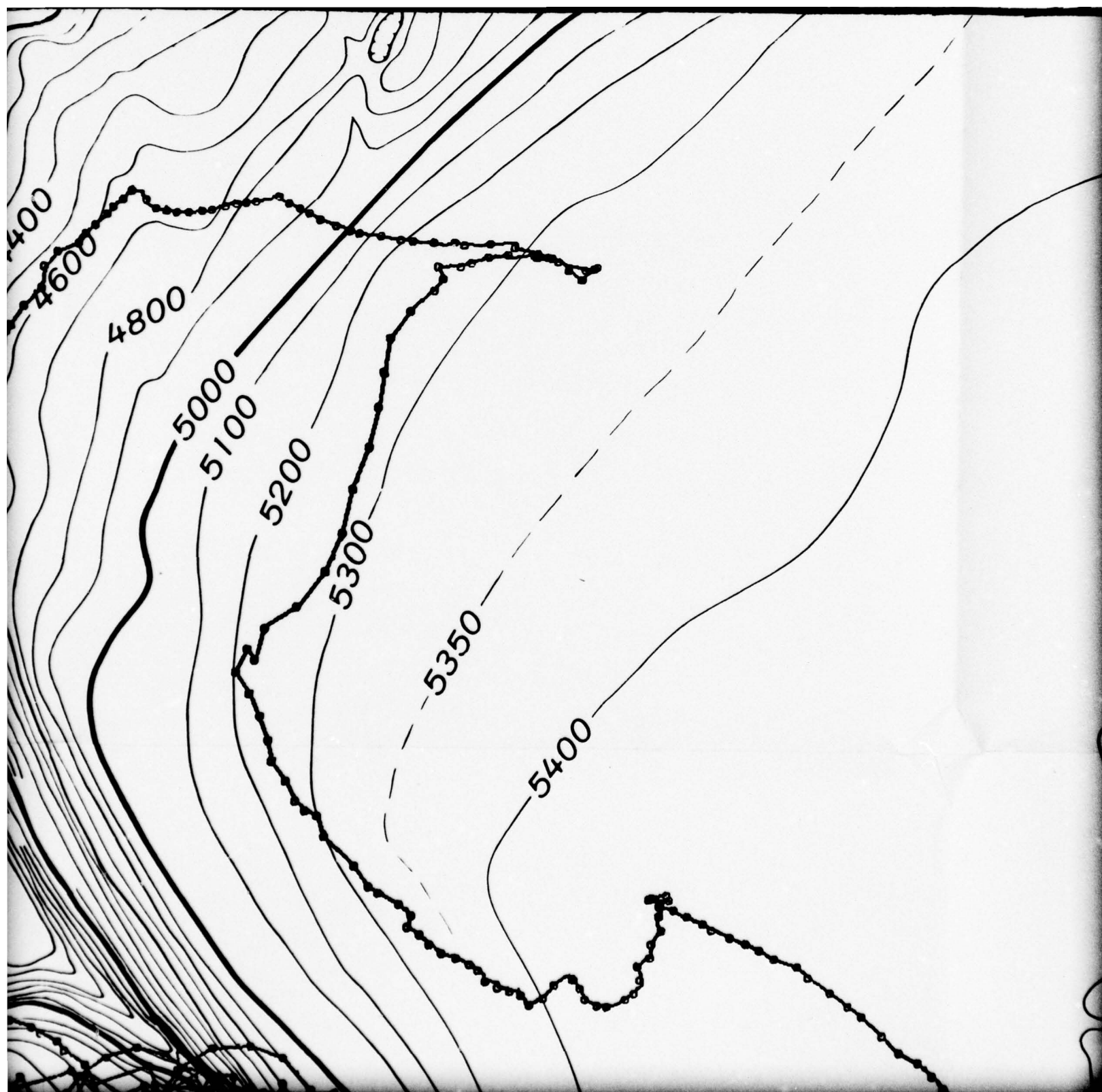
The receiving instrumentation on the islands was designed and built by Mr. Elliot Kulbersh at Yale University. We appreciate the fine support of the people operating the recording equipment on the islands, who continuously sent the tapes and drum recordings for processing. Ms. Kathy Keleher did an excellent job as data technician, coping with weak float signals and data tape problems. We also wish to thank the Yale Computer Center for their help and patience with our problems.

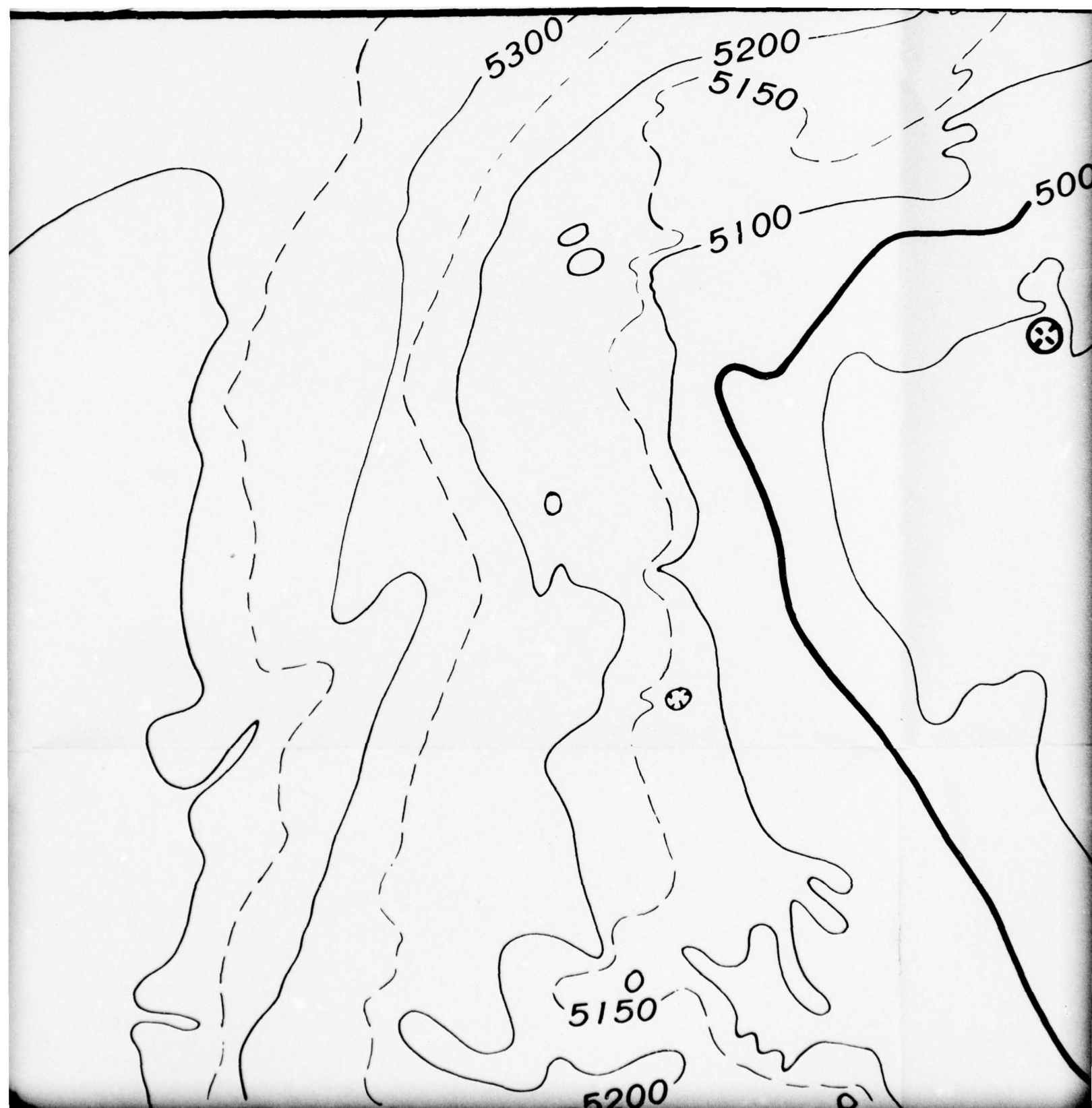
This work was funded by the International Decade of Ocean Exploration Office of the National Science Foundation under grants # 9X30220 to WHOI, # 9X30416 to Yale University, and ID075-18930 to the University of Rhode Island. The Office of Naval Research has also supported this program under contracts # N00014-67-A-0097-001 to Yale University and # N00014-76-C-0226 to the University of Rhode Island.

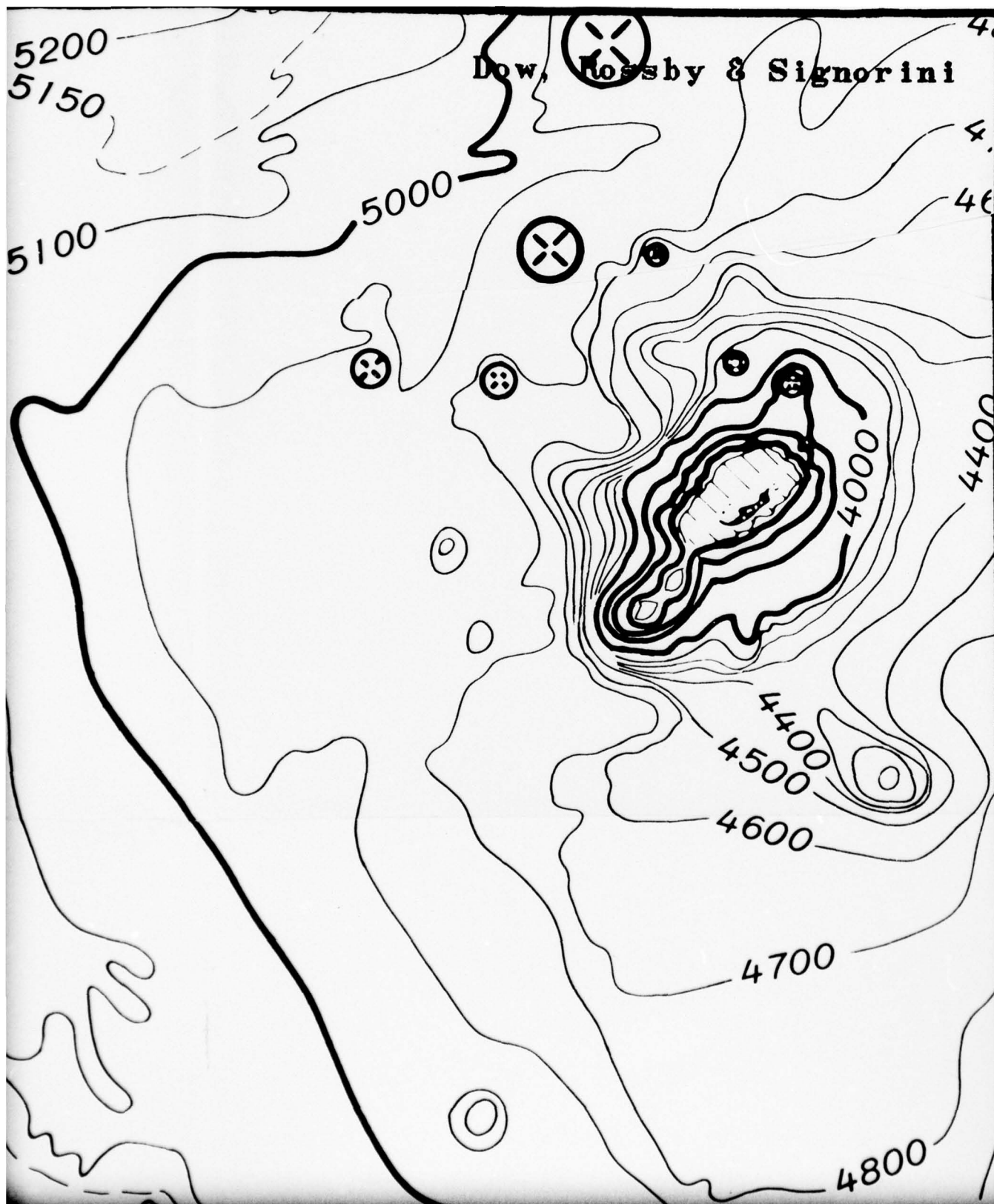
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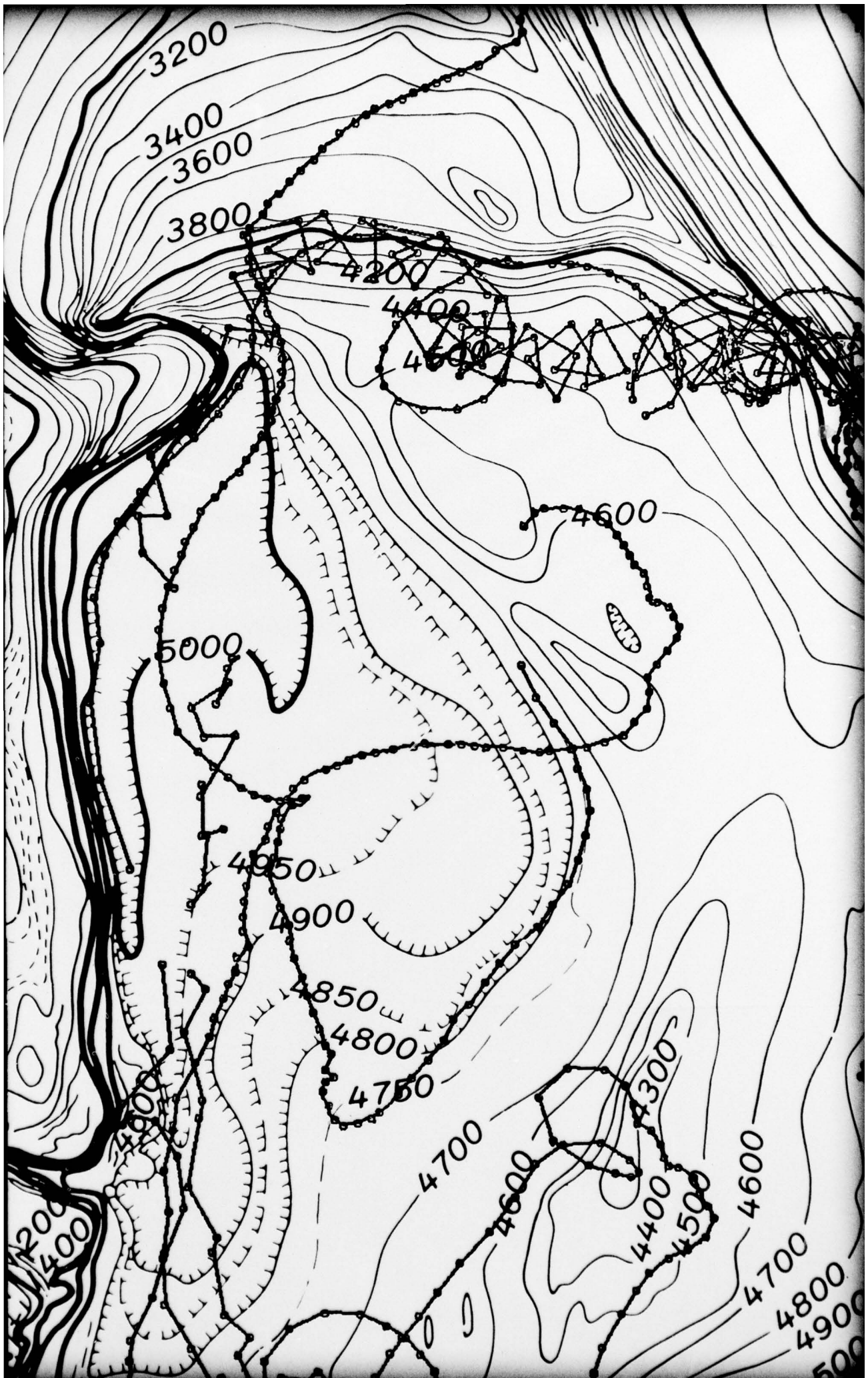
- Freeland, H.J., P. Rhines and H.T. Rossby (1975) Statistical observations of the trajectories of neutrally buoyant floats in the North Atlantic. *J. Mar. Res.* 33(3), p. 383.
- Pratt, R.M. (1968) Atlantic Continental Shelf and Slope of the United States - Physiography and Sediments of the Deep-Sea Basin, Geological Survey Professional Paper 529-B, U.S. Government Printing Office, Plate 1.
- Rossby, H.T. and D. Webb (1970) Observing abyssal motions by tracking Swallow floats in the SOFAR channel. *Deep-Sea Res.* 17, pp. 359-365.
- Rossby, H.T. and D. Webb (1971) The four-month drift of a Swallow float. *Deep-Sea Res.* 18, pp. 1035-1039.
- Rossby, H.T., A. Voorhis and D. Webb (1975) A quasi-Lagrangian study of mid-ocean variability using long-range SOFAR floats. *J. Mar. Res.* 33(3), pp. 355-382.
- Stommel, H. (1949) Horizontal diffusion due to oceanic turbulence. *J. Mar. Res.* 8, pp. 199-225.
- Stommel, H. (1955) Direct measurement of sub-surface currents. *Deep-Sea Res.* 2, pp. 284-285.
- Webb, D.C. and M.J. Tucker (1970) Transmission characteristics of the SOFAR channel. *J. Acoust. Soc. Amer.* 48, pp. 767-769.

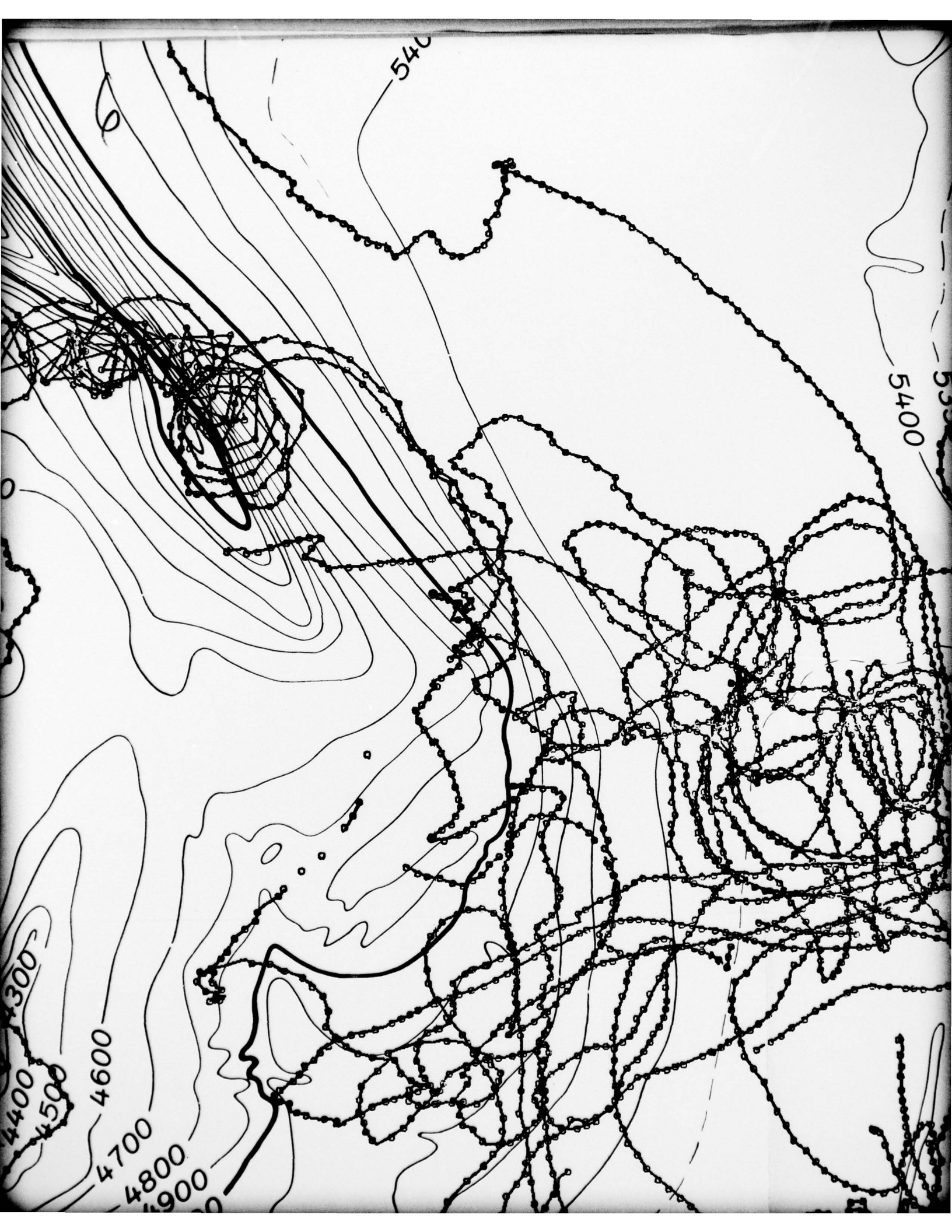


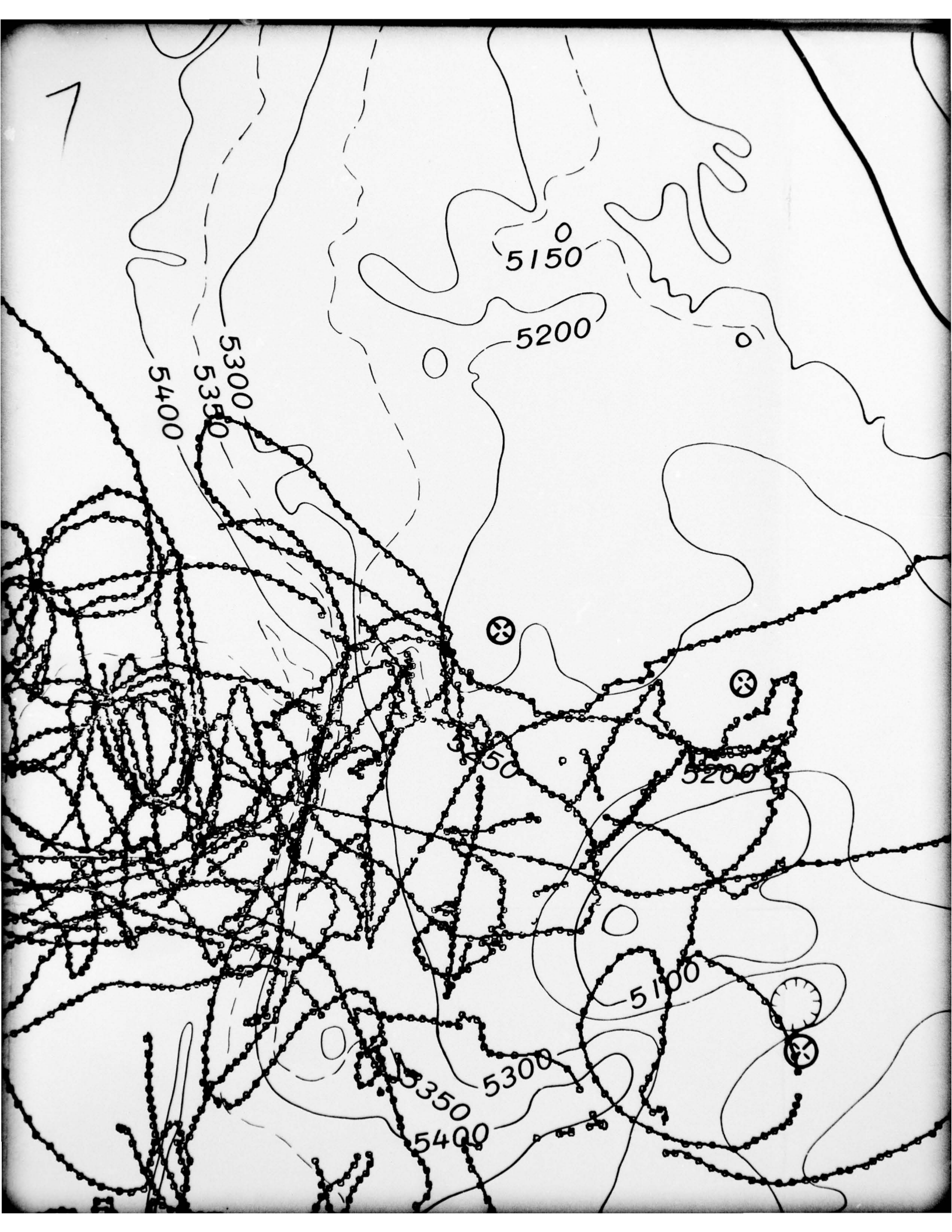


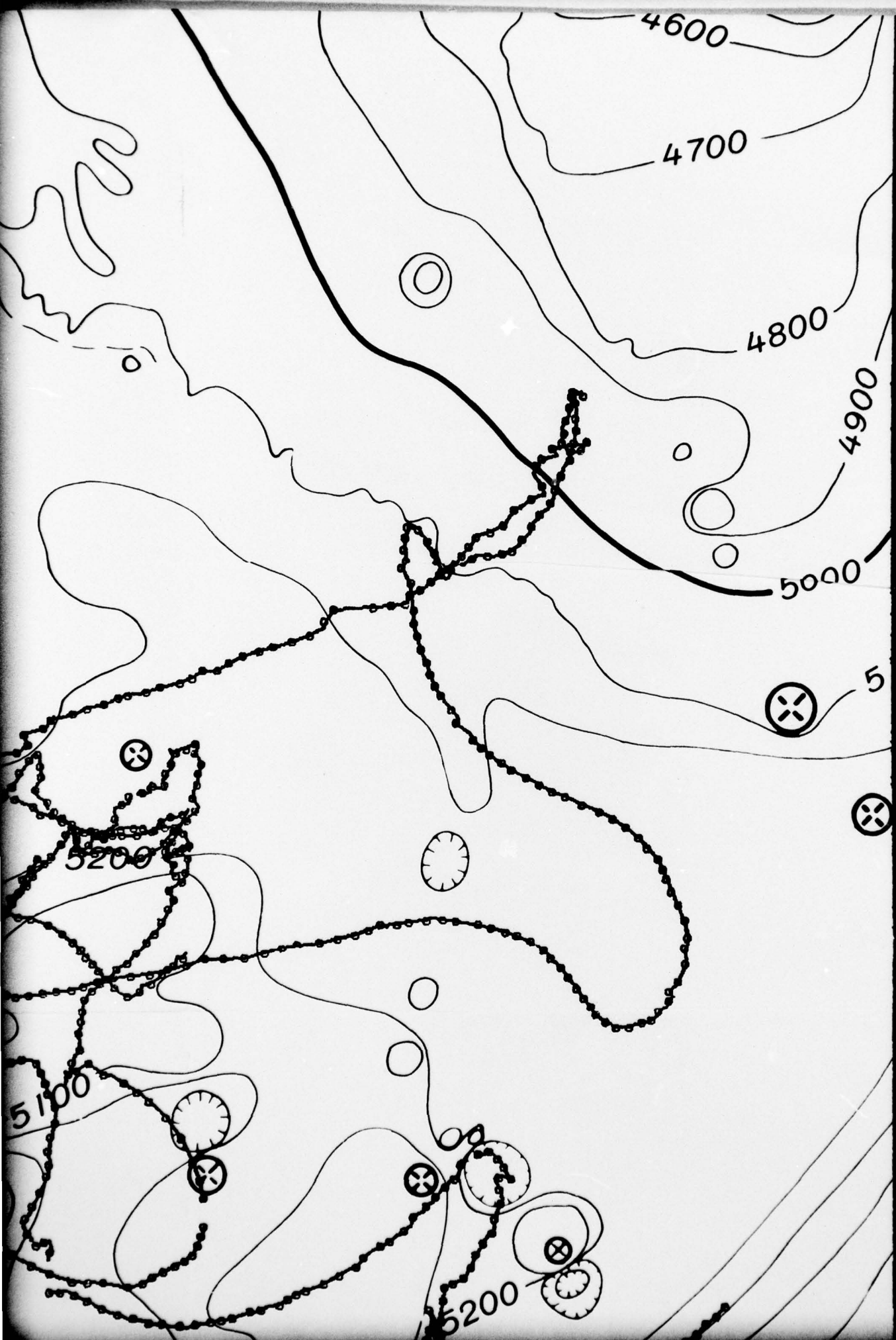












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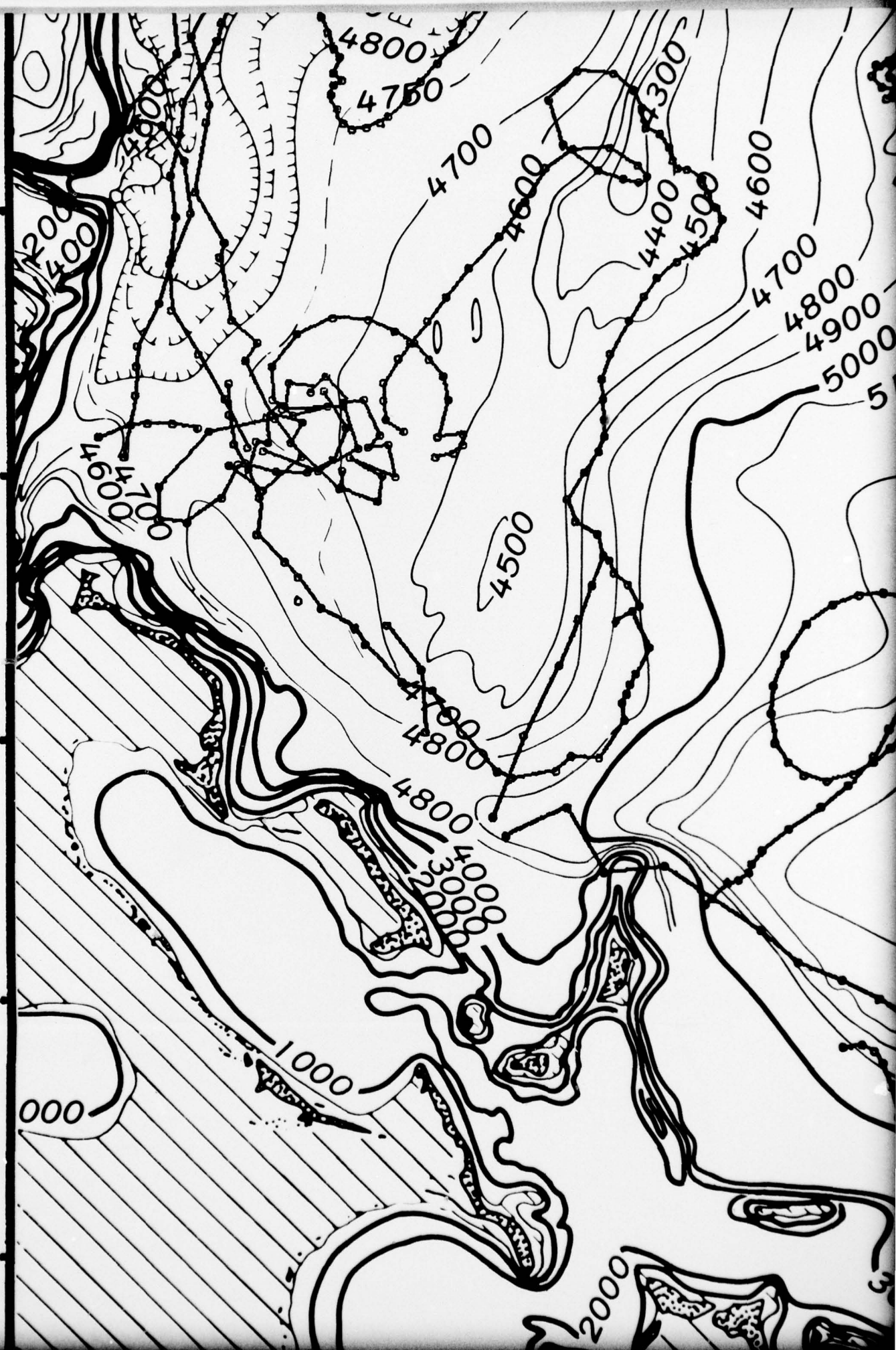
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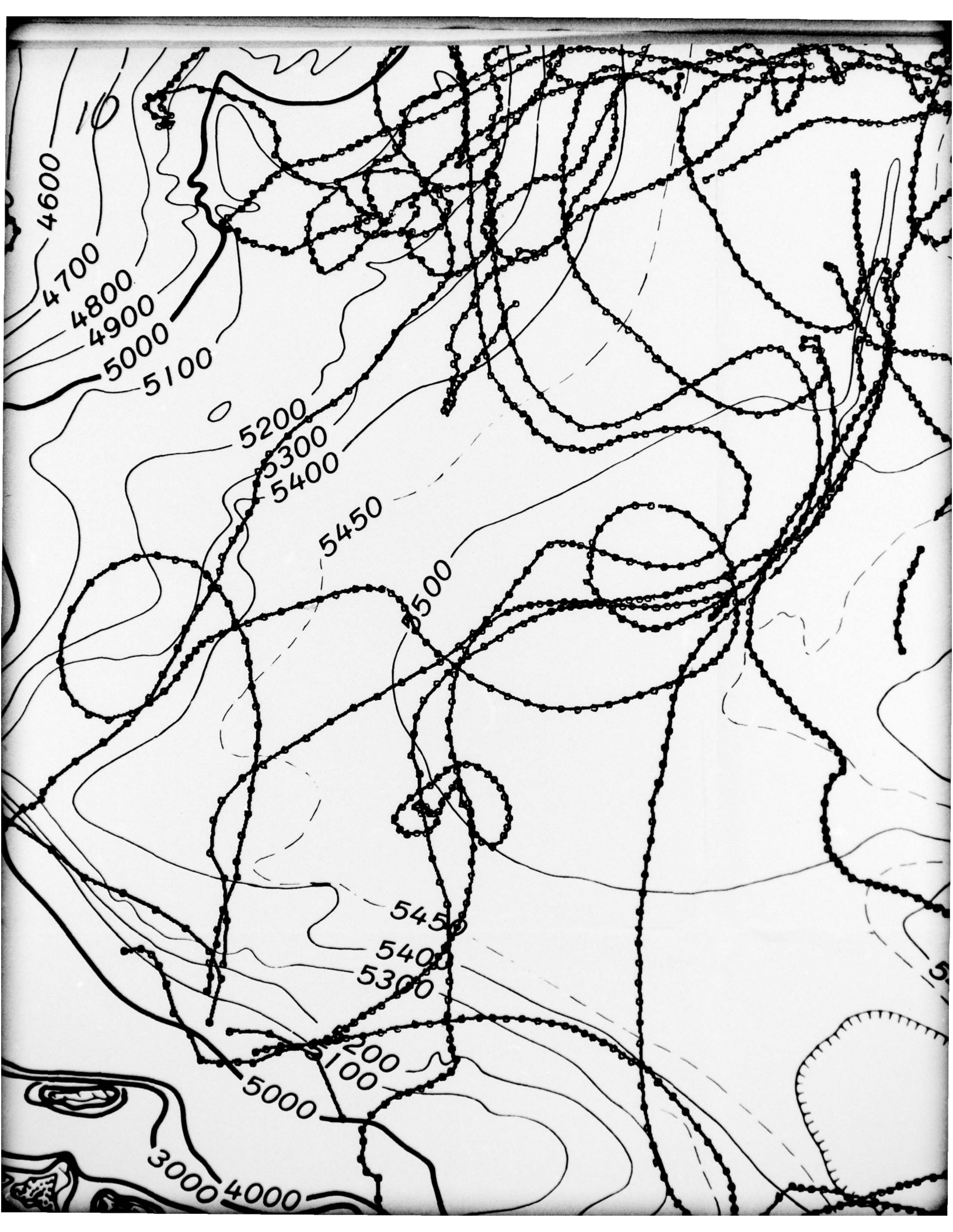
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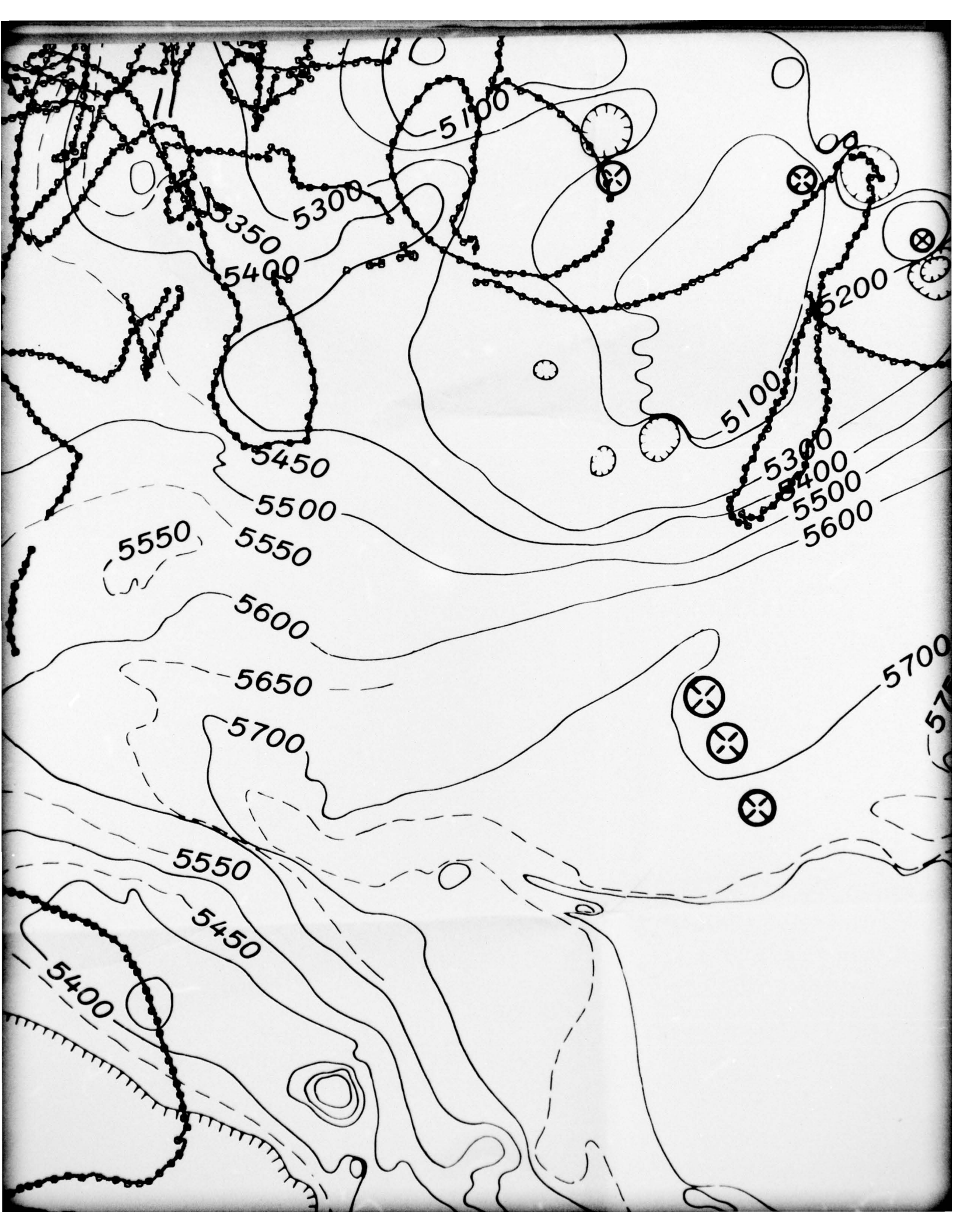
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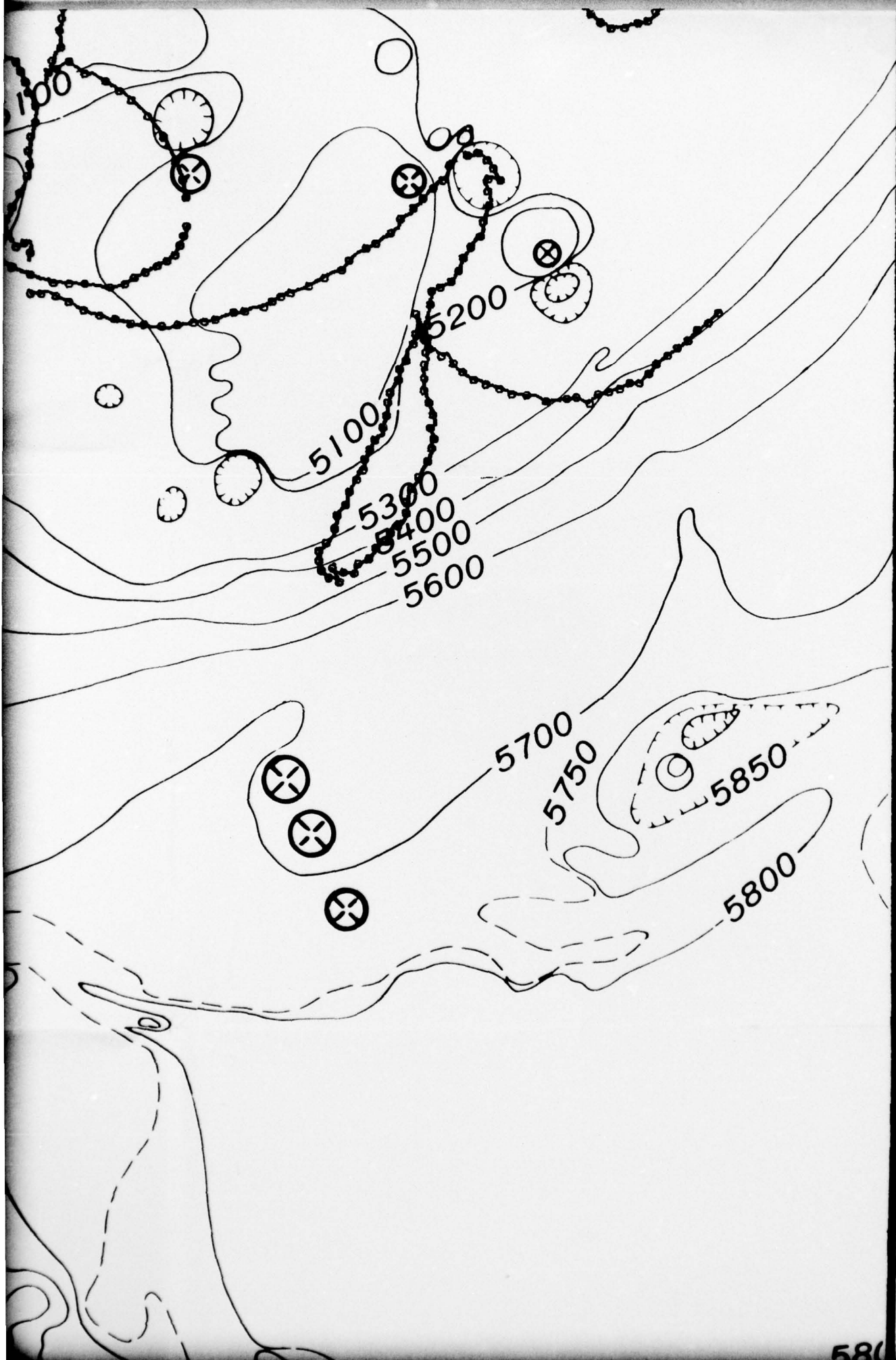
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23N





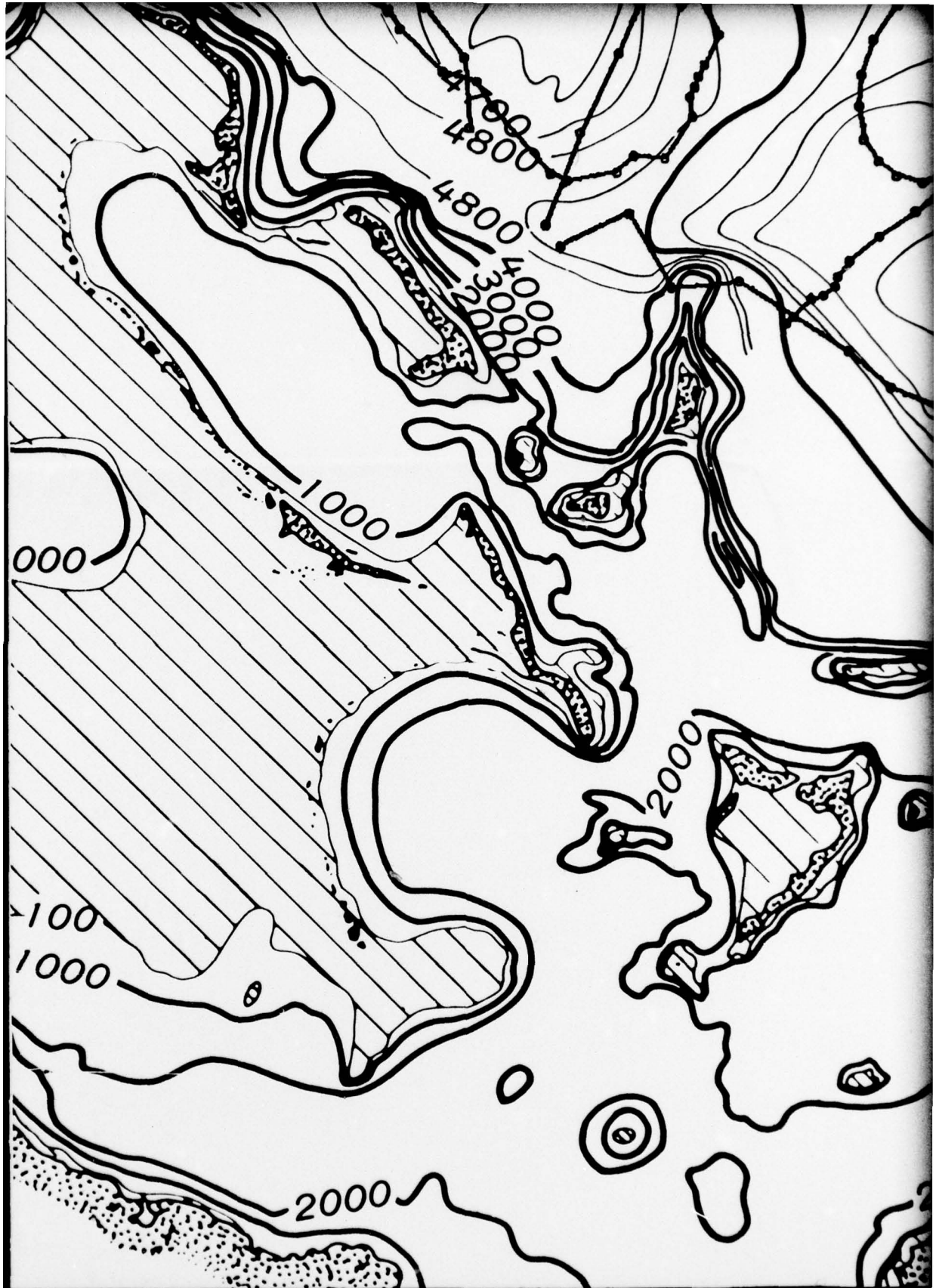


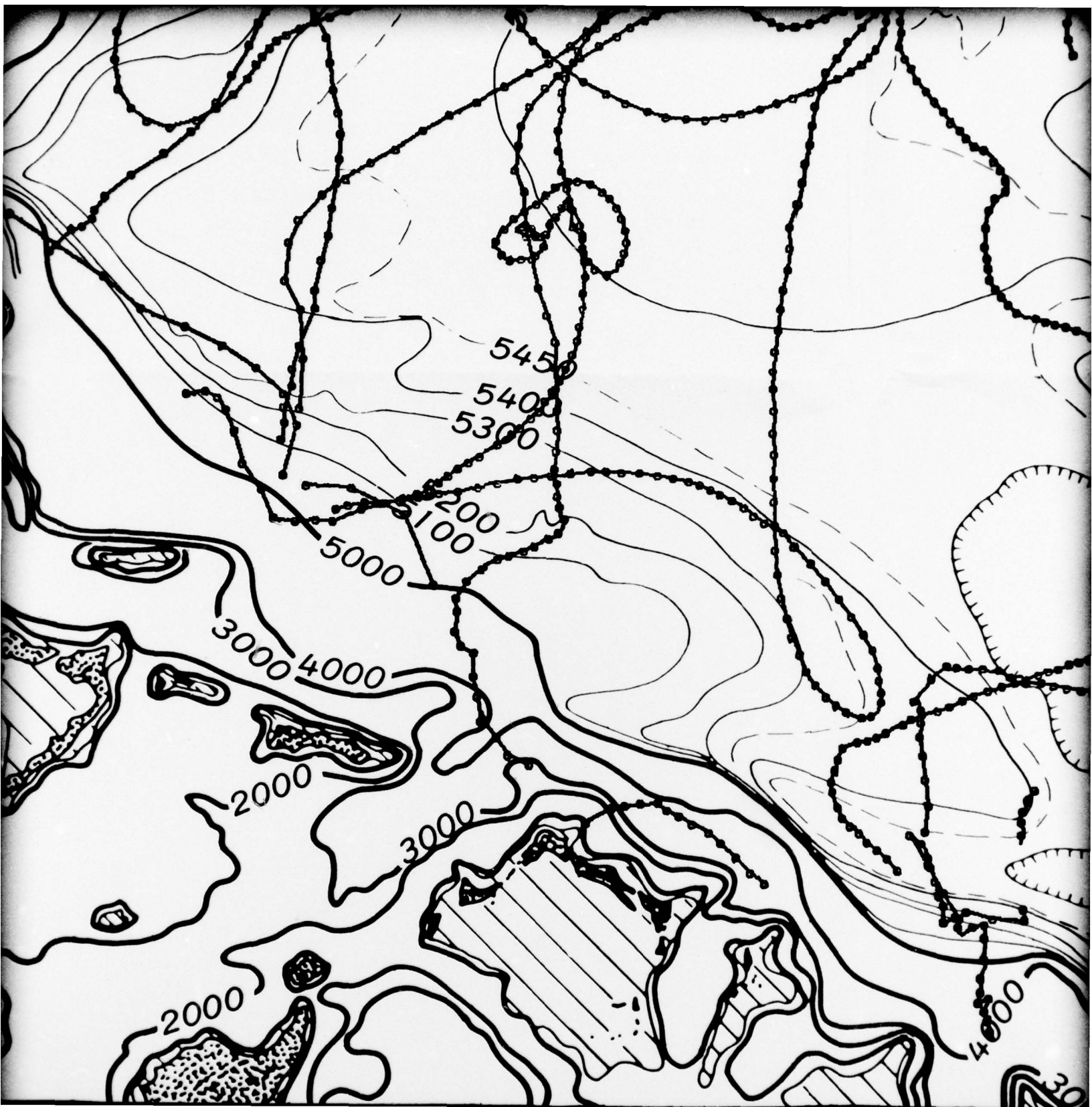


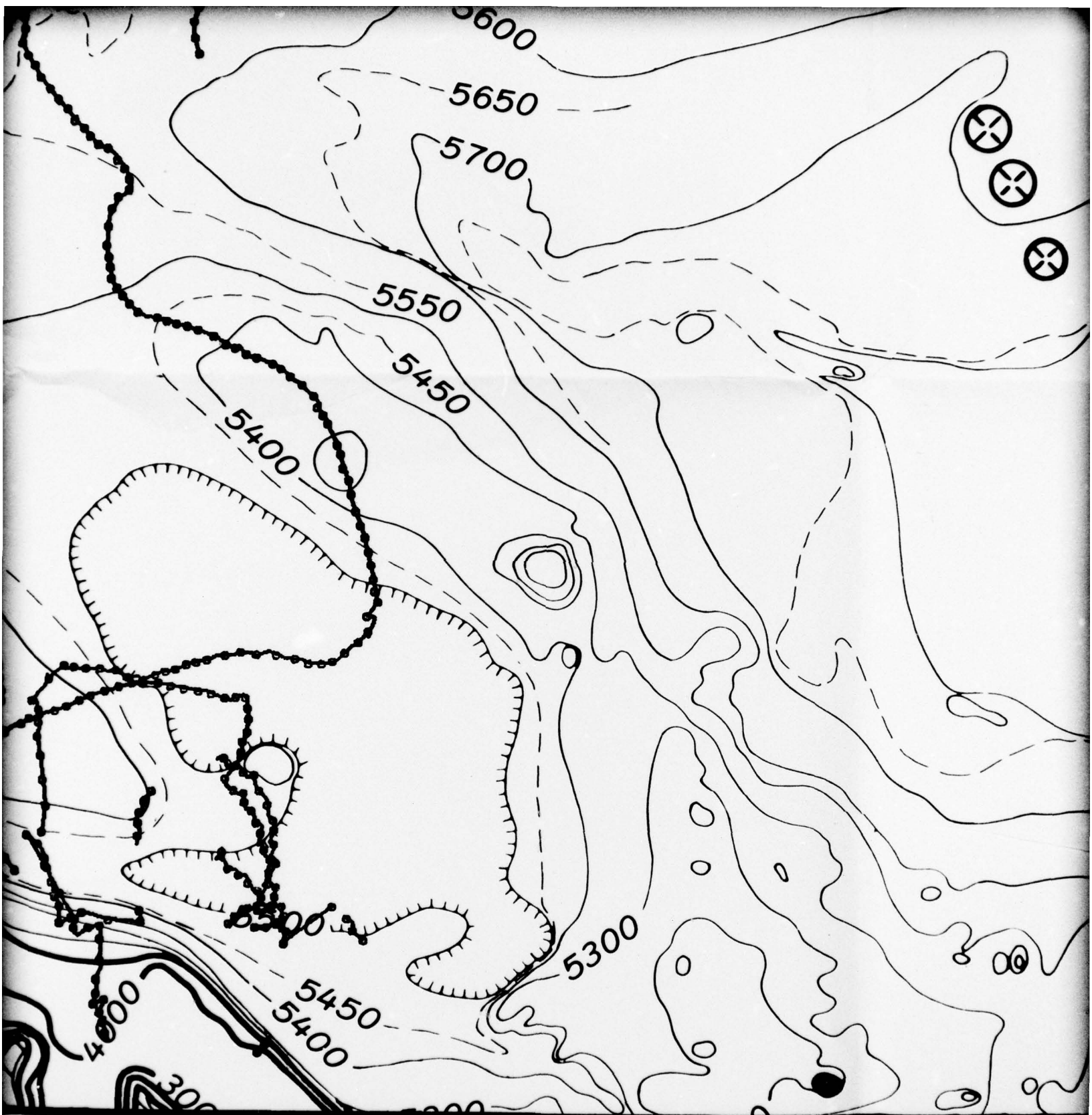
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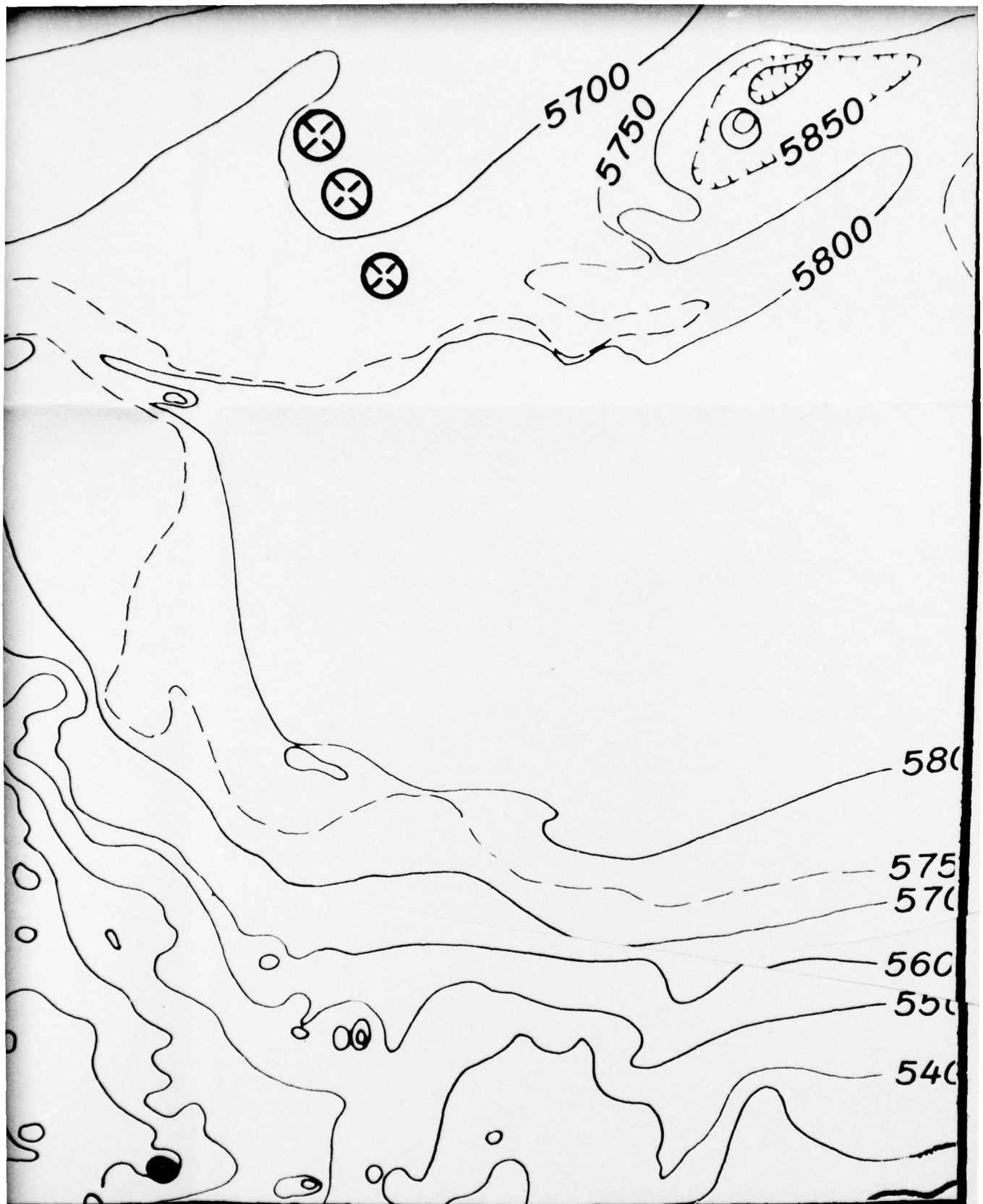
hy - Pratt (1968)

580









REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER URI/GSO Technical Report #77-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOFAR floats in MODE Final report of float trajectory data		5. TYPE OF REPORT & PERIOD COVERED Final
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This is a final report of SOFAR (Sound Fixing and Ranging) float trajectory data from MODE (Mid-Ocean Dynamics Experiment) for the period September 1972 through June 1976. It begins with a brief historical review and includes a summary of the steps involved in processing the data and computing the trajectories. The data is presented in three ways: 1. Time annotated trajec-		

20. (continued)

tories on a Mercator projection; 2. Stick plots of float velocity as a function of time; and 3. A sequence of charts, each spanning ten days, showing the spatial relationship and relative motion of all floats. There is also a table of launch, recovery, depth, number of days tracked, average velocity, speed, and kinetic energy for each trajectory.